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Proposed Recommended Practice for the Construction of Concrete Farm Silos*

Reported by ACI Committee 714

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1. SCOPE

These recommendations describe practice for use in the design and construction of concrete silos, stave, block and monolithic, for the storage of grass or corn silage.

2. GENERAL DESIGN RECOMMENDATIONS

A. Foundations

The foundation should safely support the silo and might well be one of the four following types: (1) a footing only, (2) a footing and foundation wall, (3) a battered foundation wall providing a spread footing, or (4) a foundation wall flared at the bottom on both sides, the depth of flare being at least twice the projection of the flare. When foundation walls of types 2, 3, and 4, are used, they should be at least 8 in. thick, extend at least six inches above the ground line, and should be reinforced to withstand the lateral pressure of the silage.

B. Footings

1) Depth below ground line: The distance from the ground line to the base of the footing should be at least 2 ft. in localities in which the ground freezes to a depth of 1 ft. or more.

2) Width and depth of footings: The footing should be sufficient to carry the weight and friction load of the silo. The width and depth,

*This report, approved by a substantial majority of the members of Committee 714 has been released by the Standards Committee for publication and discussion. Mr. Gurney makes special acknowledgment of the considerable labors of the Committee under the leadership of C. A. Hughes whom he succeeded as chairman in 1941 after the resignation of Professor Hughes following his entry into the Canadian Army. Professor Hughes had already submitted a draft of this report substantially as it now stands.

therefore, depend upon the height of the silo and the load carrying capacity of the soil. Recommended footing sizes are given in Tables 1 and 2 for three different types of soil. See Appendix-B.

3) Future Increases in height of silo: The footings should be designed to take care of any contemplated future increase in the height of the silo.

C. Hoop Spacing

The hoop spacing for either grass or corn silage of moisture content not over 75 percent should not exceed that given in Table 3. See Appendix-A.

D. Floors

A concrete floor may be provided for the purpose of facilitating drainage. If provided, it should be at least four inches thick, should slope toward the drain and be constructed to permit free movement relative to the walls.

E. Drains

The Committee recognizes the desirability of drains but does not feel justified in making recommendations until research now under way is concluded. Where a drain is provided, provision should also be made to carry liquids away from the site.

F. Roofs

Whether or not the silo is roofed should be optional with the purchaser. If a roof is provided, it is recommended that it have a permanent opening not less than one square foot for ventilation.

TABLE 1. DIMENSIONS OF ANNULAR FOOTINGS FOR SILOS WITH WALLS 2.5 INCHES THICK

Height of Silo ft.	TYPE OF SOIL					
	Sand and Gravel (Type 1)		Firm clay, wet sand or clay and sand mixture (Type 2)		Soft Clay (Type 3)	
	Width Inches	Depth Inches	Width Inches	Depth Inches	Width Inches	Depth Inches
20	12	8	12	8	12	8
25	12	8	12	8	18	8
30	12	8	12	8	24	8
35	12	8	16	8	32	11
40	12	8	21	10	Silos Higher Than 35 ft. Not Recommended on Type 3 Soil	
45	13	9	26	13		
50	16	11	32	15		
55	19	13	Silos Higher Than 50 ft Not Recommended on Type 2 Soil			
60	23	16				

See Appendix - B.

TABLE 2. DIMENSIONS OF ANNULAR FOOTINGS FOR SILOS WITH WALLS 6 INCHES THICK

Height of Silo ft.	TYPE OF SOIL					
	Sand and Gravel (Type 1)		Firm clay, wet sand or clay and sand mixture (Type 2)		Soft Clay (Type 3)	
	Width Inches	Depth Inches	Width Inches	Depth Inches	Width Inches	Depth Inches
20	12	8	12	8	17	8
25	12	8	12	8	24	8
30	12	8	16	8	32	11
35	12	8	21	10	Silos Higher Than 30 ft. Not Recommended on Type 3 Soil	
40	13	9	26	13		
45	16	11	32	15		
50	19	13	Silos Higher Than 45 ft. Not Recommended on Type 2 Soil			
55	23	16				
60	27	18				

See Appendix - B.

If a concrete roof is used, the design and construction should be such that no radial thrust is applied to the silo walls. The minimum concrete cover for reinforcement should be one inch.

G. Chutes

The type of chute, if used, should be optional with the purchaser. Ventilation of the barn through the chute should be avoided.

3. MATERIALS

A. Aggregates

Aggregates for use in the construction of silos should conform to the "Standard Specifications for Concrete and Reinforced Concrete" of the Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete. The total of deleterious materials of an expansive nature such as shale, absorptive chert, etc., should not exceed 1 percent by weight in aggregate coarser than the No. 4 sieve nor more than 2 percent by weight in aggregate finer than the No. 4 sieve. For aggregates for interior finishes and mortar for laying blocks see Sections 3-F and 5-F respectively.

B. Cement

Cement for use in the construction of silos should conform to the current specifications for Portland Cement of the American Society for Testing Materials.

C. Steel

Metal reinforcement for use in the construction of silos should conform to Building Regulations for Reinforced Concrete (ACI 318-41) or "Standard Specifications for Concrete and Reinforced Concrete" of

TABLE 3—HOOP SPACING FOR CONCRETE STAVE SILOS

Based upon round rods of the sizes indicated of intermediate grade steel, with rolled threads. If cut threads are used the ends must be upset, or the spacing be closer. Unit tensile stress 20,000 psi (c)

Distance from top of silo in feet	Lateral Pressure of silo in psf (a) (c)	Hoop Spacing in Inches for 9/16 Inch Diameter Rods — Silo Diameter in feet						Hoop Spacing in Inches for 1/2 or 9/16 Inch Diameter Rods — Silo Diameter in feet					
		10	12	14	16	18	20	10	12	14	16	18	20
2½	12	30	30	30	30	30	30	30	30	30	30	30	30
5	33	30	30	30	30	30	30	30	30	30	30	30	30
7½	60	30	30	30	30	30	30	30	30	30	30	30	30
10	91	30	30	30	30	30	30	30	30	30	30	30	30
12½	125	30	30	30	30	30	30	30	30	30	30	30	30
15	162	30	30	30	30	30	30	30	30	30	30	30	30
17½	203	30	30	30	30	30	30	30	30	30	30	15	15
20	246	30	30	30	30	15	15	30	30	15	15	15	15
22½	294	30	30	30	15	15	15	30	15	15	15	15	15
25	340	30	30	15	15	15	15	15	15	15	15	15	15
27½	388	30	15	15	15	15	15	15	15	15	15	15	15
30	440	15	15	15	15	15	10	15	15	15	15	15	10
32½	495	15	15	15	15	10	10	15	15	15	15	10	10
35	550	15	15	15	10	10	10	15	15	15	10	10	10
37½	609	15	15	10	10	10	10	15	15	10	10	10	10
40	668	15	15	10	10	10	7½	15	15	10	10	10	7½
42½	725	15	10	10	10	7½	7½	15	10	10	10	7½	7½
45	793	15	10	10	7½	7½	7½	15	10	10	7½	7½	7½
47½	855	10	10	10	7½	7½	6	10	10	10	7½	7½	6
50	925	10	10	7½	7½	7½	6	10	10	7½	7½	7½	6
52½	990	10	10	7½	7½	6	6	10	10	7½	7½	6	6
55	1055	10	7½	7½	6	6	6	10	7½	7½	6	6	6
57½	1110	10	7½	7½	6	6	5	10	7½	7½	6	6	5
60	1200	7½	7½	6	6	5	5	7½	7½	6	6	5	5

(a) See Appendix - A.
(b) For spacings above zig-zag line use ½ inch rods. For spacings below zig-zag line use 9/16 inch rods.
(c) psi denotes pounds per sq. in., psf denotes pounds per sq. ft.

the Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete.

D. Concrete

1) Proportioning, mixing, curing and testing concrete: Proportioning mixing, curing and testing concrete should be in conformance with the provisions relating thereto of the "Recommended Practice and Standard Specifications for Concrete and Reinforced Concrete" of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete.

2) Concrete quality: It is recommended to ensure a high degree of imperviousness and durability, that the concretes used in various parts of the silo should have compressive strength not less than that given in the following table:

Location	Minimum Recommended Compressive Strength at 28 days psi
Footings	3,000
Foundation Walls	3,500
Silo Wall, Roof, Door Frames & Chute	4,500

E. Hoops

1) Effective area: The effective area of threaded rods for stress calculation should be based on the diameter at the root of threads when cut threads are used and should be based on the diameter of the rod when rolled threads are used.

2) Design unit stress: The unit stress for design should be 18,000 psi for structural, 20,000 psi for intermediate grade steel bars and not more than 50 percent of the minimum value for the yield point given in the specification governing any special steels that may be used.

3) Hoop-spacing: The spacing of hoops should be such that the lateral pressures given in Table 3 will not cause unit stresses in excess of the design unit stress of the paragraph next above. The spacing used should conform as closely as possible to the spacing shown in Table 3.

4) Lugs: Lugs (connections for hoops of round cross-section) should be of malleable cast iron or of steel. The strength of the lug should be such that the ultimate strength of the hooping to be used with it can be developed by the lug in place. For silo diameters up to and including ten feet, at least two lugs per hoop should be used; for diameters from 10 to and including 16 ft., at least three lugs per hoop should be used; and for diameters from 16 to and including 22 ft., at least four lugs per hoop should be used.

5) Connections: Connections for flat hoops should develop in place twice the design load of the hoops. The number of connections per hoop should be not less than the number of lugs per hoop recommended in the paragraph next above.

6) Tightening hoops: The hoops should be uniformly tightened to about 50 percent of the design stress, the joints filled, the fillings allowed to harden, and the hoops again tightened, this time to full stress. Before the silo is filled the hoops on the lower two-thirds of the silo preferably should be retightened.

7) Spreaders: Spreaders should develop in place twice the design load of the hoops connected to them.

F. Interior finishes

Concrete stave silos should, and other concrete silos may, be plastered or given a cement wash inside in order to make them more nearly impervious. Materials for this should be prepared and applied as here recommended.

1) Cement plaster: The grading of the sand should be within the following limits: All material passing No. 4 sieve; from 15 to 35 percent retained on No. 14 sieve, and from 65 to 85 percent retained on No. 48 sieve.

Fine sand should be added to natural sand that is deficient in fines. The sand used in plaster coat should have not more than ½ percent of shale and other expansive material by weight. The mix should be 1 part of portland cement to 1½ parts of sand by weight. Retempering of the mix should not be permitted.

The wall should be wet down prior to plastering in such a manner that a proper and uniform suction is obtained. Immediately prior to applying the plaster, a thin cement grout should be well brushed into the wall surface. The plaster coat should vary uniformly from an average thickness of ¼ inch at the top to ½ inch at the bottom. It should be protected from abrasion and too rapid drying for at least three days.

2) Cement wash: Cement wash should be prepared by mixing portland cement with water to give a creamy consistency. The cement should be screened into the water to prevent lumping. The wash should be applied to clean and dampened walls. It should be protected from abrasion and too rapid drying for at least three days.

4. STAVE SILOS

A. Quality of staves

Staves used in silos should conform to the following Specifications:

1) Flexural strength: The average flexural strength of five staves at the time of delivery shall be not less than 690* psi and the flexural strength of an individual stave shall be not less than 660 psi.

2) Absorption: The absorption after submersion in water for 24 hours shall not exceed 6 percent by weight.

3) Minimum thickness: No stave shall have a thickness at any section less than 2.0 inches.

*This represents 120 lb. per inch of width on a 2.5-in. thickness of plane-faced stave.

4) Marking: All silos shall bear a distinctive mark of the manufacturer of the staves used in its construction.

5) Inspection: Proper facilities shall be provided the purchaser for sampling and inspection either at the factory or at the site of work, whichever may be specified in the contract. At least ten days from the time of sampling shall be allowed for the completion of the tests. All tests shall be made in accordance with the methods specified in sections 12 and 13.

6) Expense of tests: The expense of inspection and testing shall be borne by the purchaser, unless otherwise specified in the contract.

7) Selection of staves for test: Staves for testing shall be selected by the purchaser or by a competent representative authorized by him to do this work. Such staves shall be representative of the lot of staves from which they are selected. Full size staves shall be used in all cases.

8) Number of staves per sample: The sample for testing shall consist of five full size staves.

9) Marking: All staves selected for testing shall be permanently identified before shipment to the laboratory.

10) Moisture content at time of test: The staves shall be submerged in water for 24 hours prior to testing. They shall be loaded immediately after removal from submersion. Surface water may be wiped off with a damp cloth.

11) Measure of thickness: The thickness of plane-faced staves shall be taken as the average of five measurements made with a thickness gage reading to 1/1000 in. These measurements shall be taken along the short axis (or at the break) of the stave at one inch from each edge, at the quarter points, and at the center point. This average shall be recorded to the nearest 1/100 in.

12) Width: The width of plane-faced staves to be used in calculating the flexural strength shall be the laid-up width. This width shall be taken as equal to one fourth the distance measured between corresponding points on the first and fifth staves of five staves fitted together on a plane surface, so as to obtain the minimum over-all width.

13) Position: The stave shall be supported on a 24-in. span and loaded at midspan. The surface of the stave intended to be on the exterior of the silo shall be in tension under the test load. The end supports shall be free to rotate in directions parallel and perpendicular to the long axis of the stave and shall be sufficiently stiff so that the load is substantially uniformly distributed along their length. Padded bearing plates 2 in. wide shall be used at the supports and at the central knife-edge. The set-up shall be such that no torsional moments are developed. Special bearing blocks shall be used when testing non-planer staves.

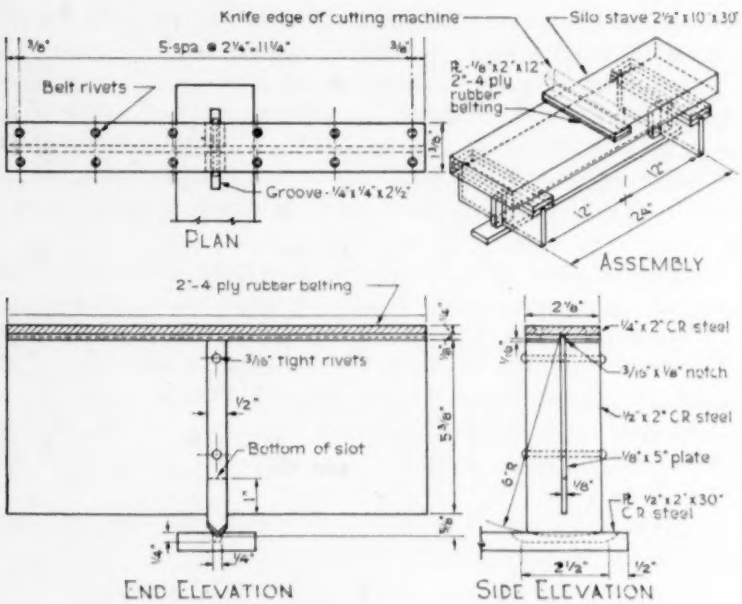

Fig. 1—Apparatus for testing silo staves

NOTE:—Fig. 1 shows the details of an apparatus for testing silo staves, which comlies with this specification.

14) Speed of loading: The speed of the moving head of the testing machine shall not be more than 0.05 in. per minute.

15) Flexural strength: The flexural strength of plane-faced staves shall be determined by the following calculation:

$$\text{Flexural strength in psi} = \frac{36W}{bd^2}$$

The flexural strength of staves with non-planer faces shall be determined by the following formula:

$$\text{Flexural strength in psi} = \frac{6Wc}{I}$$

in which W = the maximum load in pounds
b = the width of plane-faced staves
d = the thickness of plane-faced staves
c = the distance from neutral axis to extreme tensile fibre in inches
I = the moment of inertia of a section normal to the long axis of the stave in inches to the fourth power.

16) Absorption samples: The sample for the absorption test shall consist of one of the two pieces (approximately a half-stave) of each of the five staves which result from the flexure test.

17) Marking: Each piece shall be marked so that it may be identified at any time with the stave from which it was taken. The marking shall not cover more than 5 percent of the area of one face of the half-stave.

18) Drying: The pieces shall be dried in an oven at a temperature between 100 and 110 C. (212 and 230 F.) and weighed at 24-hour intervals until the loss in weight does not exceed 0.2 percent of the previous weight.

19) Accuracy of balance: The balance used shall be sensitive to within 0.05 percent of the weight of the smallest piece tested.

20) Immersion: The dry weights of the pieces shall be obtained after which they shall be immersed in water at room temperature (60 to 80 F.), for 24 hours. They shall be removed from the water and allowed to drain for 60 seconds by placing on $\frac{3}{8}$ in. or coarser wire mesh, visible surface water being removed with a damp cloth, and immediately weighed.

21) Percent absorption: The absorption is the difference between the wet and dry weight of the sample divided by the dry weight and multiplied by 100.

B. Joints

The joints of stave silos should be closed by pointing with cement paste or mortar, by cement washing or by plastering—one or more; or, if special joints are used, by pouring. See Sec. 3, F.

5. BLOCK SILOS

A. General

Block silos are those built of precast concrete units other than staves.

B. Quality of blocks

Hollow blocks should conform to the current "Standard Specifications for Hollow, Load-Bearing Concrete Masonry Units" of the American Society for Testing Materials, for the grade of block having a minimum compressive strength on the gross area of 1,000 psi. Solid blocks should conform to current "Standard Specifications for Solid Load-Bearing Concrete Masonry Units" of the American Society for Testing Materials, for Grade A blocks, having a minimum compressive strength on the gross area of 1,800 psi.

C. Minimum dimensions

The over-all thickness of the blocks as laid in the wall should not be less than 6 inches and the face shell thickness should not be less than $1\frac{1}{2}$ inches.

D. Provision for lateral pressures

External hooping, spaced not farther apart than every second course, should be provided to withstand the whole lateral pressure due to the ensilage. (See Table 4 for lateral pressures.)

E. Provision for vertical load

The maximum unit compressive stress on the net area due to the vertical load should not exceed fifty percent of the compressive strength of the unit.

F. Mortar

The mortar used for laying up the blocks should not be leaner than one of portland cement to two of plaster sand by weight. Fully bedded joints should be used. The aggregate should contain not more than ½ of 1 percent of shale and other expansive material. See Sec. 3 A.

6. MONOLITHIC SILOS

A. Wall thickness

The wall thickness measured in a radial direction should not be less than 4 inches if external hooping is used; and of such thickness that the metal reinforcement is protected both inside and outside by not less than 2 inches of concrete if embedded reinforcement is used.

B. Construction joints

Whenever it is necessary to interrupt the placing of the concrete for walls for more than two hours, the concrete should be levelled and its surface roughened by brooming after set has started but before the concrete has appreciably hardened. Just before placing is resumed, a thin cement paste should be brushed into the surface of the previously placed concrete.

APPENDIX

A. Lateral pressures and hoop spacing

The lateral pressures of silage given in Table 4 comprise all the lateral pressure data known to the Committee. These data were obtained in a research study in which U. S. Department of Agriculture, the New Jersey Agricultural Experiment Station, the National Association of Silo Manufacturers, and the Portland Cement Association cooperated. The work was done at the Dairy Research Farm, Sussex, New Jersey. The data include results from four tests using corn silage and 12 tests using grass silage. The grass silage data have been separated into two groups, alfalfa and peas, according to the chief material ensiled. Variables other than those shown in Table 4 were included in the investigation.

The data of Table 4 are plotted in Fig. 2, from which it is at once evident (a) that the relation between lateral pressure and head of silage is expressed by a curved line and (b) that there is no justification for assigning different pressure relations to different ensiled materials. Study of the data indicates clearly that lateral pressures increase with moisture content and with the diameter of the silo. It should be noted also that no data exist for silage heads greater than 40 ft. In the past, the silo industry has used equivalent fluid weights of 11 lb. per cu. ft. for

TABLE 4—LATERAL PRESSURE OF SILAGE

Silo No.	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV	XVI
Ensiled Material	Corn					Alfalfa								Peas		
Moisture Content	70%	81%	74%	74%	71	70	78	66	71	68	68	77	77	64	74	72
Diameter of Silo	14′-0″	16′-0″	18′-0″	18′-0″	11.6	12	12	14	14	18	18	18	18	12	14.3	18
Reference	B	A	A	C	A										A	
h																
5	46	37	36	38	46	27	48	40	28	29	36	33	30	23	49	38
10	84	109	107	97	92	77	193	83	91	94	97	106	111	63	110	113
15	143	200	171	166	138	132	322	112	142	170	153	213	215	90	179	192
20	178	332	238	266	185	169	427	152	193	242	215	334	350	117	251	277
25	218	498	299		258	196	477	209	239	337	295	500	544	159	314	376
30	234	645	391			220	550	281	302	527	349	601	759		381	464
35	280	760	457			268	570	310	414			730	974			610
40	320	900	570			338	696		520			950	1189			734

Reference A—Mimeographed paper entitled "Observations on the Storage of Grass Silage" by H. E. Besley and J. R. McCalmont, presented at the annual convention of the NASM, Chicago, Dec. 2, 1940.

B—A photographic print entitled "Silo Investigations", by Bureau of Agricultural Chemistry and Engineering, USDA, Washington, D. C.

C—Mimeographed paper entitled "A Progress Report". New Jersey Silo Research Project by H. E. Besley, W. L. Humphries, J. R. McCalmont, and W. H. Tamm. 1940.

corn silage and 20 lb. per cu. ft. for grass silage. The two heavy straight lines on Fig. 2 represent the pressure-head relations of these equivalent fluid weights. The 20-lb. per cu. ft. relation is conservative for low heads and is not suitable for extrapolation.

Because silos are built with heights greater than 40 ft., extrapolation becomes a practical necessity. Knowing the dangers of extrapolation, the curve of best fit was obtained by least square. This is the heavy curved line of Fig. 2 marked $L=3.3h^{1.44}$ in which $L=$lateral pressure in psf and $h=$vertical distance in feet from the point at which pressure is determined to the top of the silage. The lateral pressure of either grass or corn silage of moisture content not exceeding 75 percent should be calculated by this formula.

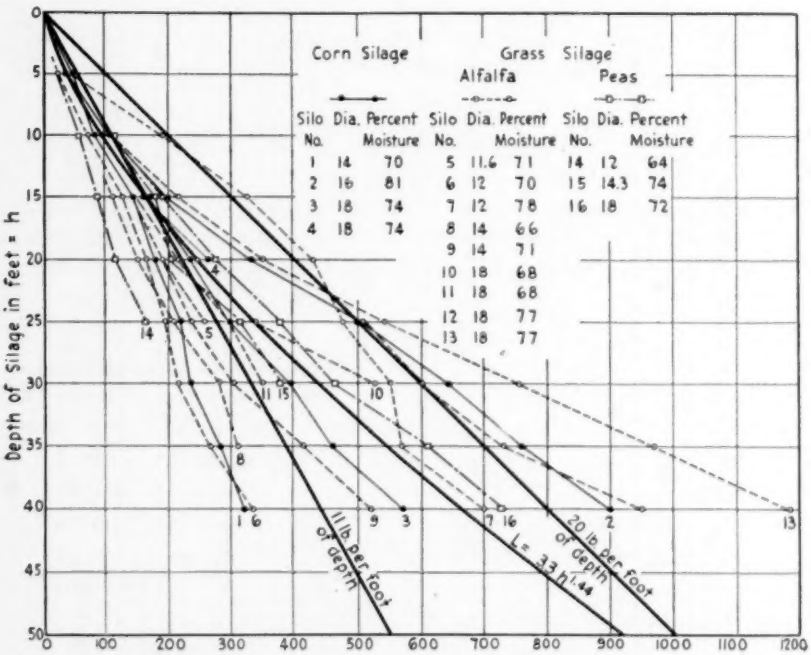

Fig. 2—Lateral pressure in pounds per square foot = L

The regression lines were nearly parallel, indicating good correlation between this curve and the data. The apparent accuracy with which the equation is expressed does not, of course, indicate that the formula will tell closely the pressure in a given silo. It is evident from Fig. 1 that the lateral pressures for individual silos may vary widely from those given by the equation. A method of calculating silo pressures which includes the major variables, such as diameter and moisture content,

is highly desirable, but such a formula has not been developed, nor is the data required for its development available at the present time.

Referring again to Fig. 2, it will be seen that the lateral pressures for silos 2, 12, and 13 are markedly in excess of the lateral pressures of the curve and also that the moisture contents were 81, 77, and 77 percent respectively. For this reason, the use of the equation $L=3.3h^{1.44}$ has been limited in the "Practice" to silage having moisture contents of 75 percent or less.

The use of silage of higher moisture content would not cause collapse of the silo but might do damage requiring repairs before refilling. Using the data for silo 13 as an example, its lateral pressure at a 40-ft. head is 1.78 times the curve pressure. Assuming a unit stress of 20,000 psi in the hooping for the curve pressure, the unit stress in silo 13 would be 20,000x1.78=35,600 psi, a unit stress within the elastic limit. The strain in the steel would unquestionably exceed the elastic recovery of the concrete, and in consequence, vertical cracks would develop between the staves, thus permitting leakage. The leakage will cause surface damage to both staves and hoops but will also reduce the lateral pressure. Hence no danger beyond the possibility of a local and easily repaired surface damage will result from the use of high moisture content silage in silos with hooping designed by the curve $L=3.3h^{1.4}$.

Values of the recommended lateral pressures and the corresponding hoop spacings for ½-in. and 9/16-in. diameter rods and an allowable unit stress of 20,000 psi calculated by the formula below are given in Table 3.

$$s = \frac{24 f_s A_s}{LD} \qquad (1)$$

in which s = spacing of hoops in inches
f_s = allowable unit stress in the hoop in psi.
A_s = area of hoop in sq. in.
L = lateral pressure in psf.
D = diameter of silo in feet.

B. Vertical wall loads, widths and depths of footings

Silage pressure on the silo walls has a vertical as well as a lateral component. The vertical component might also be called a friction load developed because of settlement or the tendency of silage to settle. Data for vertical loads on walls are available from the same source as for lateral loads. These data are given in Table 6 and are plotted in Fig. 3. The curve of best fit for the data of Table 6 was found to be

$$f = 5.5h^{1.08} \qquad (2)$$

in which f = vertical wall load in psf
and h = depth below top of silo in feet

TABLE 5—WEIGHTS IN POUNDS OF HOOPING REQUIRED FOR 50 FOOT SILOS

Figuros in brackets are relative weights.

Diameter of Hooping inches	Design Stress psi	Lateral Pressure psf	Diameter of Silo in Feet					
			10	12	14	16	18	20
9/16	20,000	$L = 3.3h^{1.44}$	(1.0) 851	(1.0) 1118	(1.0) 1452	(1.0) 1830	(1.0) 2200	(1.0) 2660
1/2 & 9/16	20,000	$L = 3.3h^{1.44}$	(0.92) 782	(0.93) 1041	(0.96) 1386	(0.94) 1728	(0.95) 2099	(0.96) 2567
9/16 [a]	18,000	20h	(1.25) 1062	(1.31) 1470	(1.25) 1825	(1.37) 2510	(1.41) 3110	(1.41) 3775
9/16 [a]	18,000	11h	(0.88) 745	(0.85) 958	(0.87) 1268	(0.86) 1575	(0.87) 1916	(0.84) 2238

a. Spacings used were those given in "Silo Hoopage Standards", February 29, 1940, National Association of Silo Manufacturers.

NOTE:—Weights for a combination of 1/2-in. and 5/8-in. hoops are greater than for the combination of 1/2 and 9/16 hoops.

TABLE 6—VERTICAL LOADS ON SILO WALLS DUE TO SILAGE

Silo No.	III	IV	VII	X	XI	XVI
Ensiled Material	Corn		Alfalfa			Peas
Moisture Content %	75	74	78	68	68	72
Diameter of Silo	18.0	18.0	12	18	18	18
Reference	A	C	A	A	A	A
h						
5	39	27	41	26	24	46
10	70	66	67	51	58	84
15	95	98	95	92	81	128
20	133	126	188	123	116	151
25	176		246	166	144	179
30	233		265	225	176	199
35	270		264			218
40	300		307			244

Reference A—Mimeographed paper entitled "Observations on the Storage of Grass Silage" by H. E. Besley and J. R. McCalmont, presented at the annual convention of the NASM, Chicago, Dec. 2, 1940.

C—Mimeographed paper entitled "A Progress Report". New Jersey Silo Research Project by H. E. Besley, W. R. Humphries, J. R. McCalmont, and W. H. Tamm. 1940.

The vertical load per foot of circumference at a distance h is given by

$$F = \int_0^h 5.5h^{1.08} = 2.64h^{2.08} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

For a vertical cylindrical wall centered on an annular footing of any type the width at the base of the footing required to support the wall and vertical friction loads is given by formula (4):

$$w = \frac{12h_1}{p}\,(12.5t+2.64h^{1.08}{}_1) \qquad (4)$$

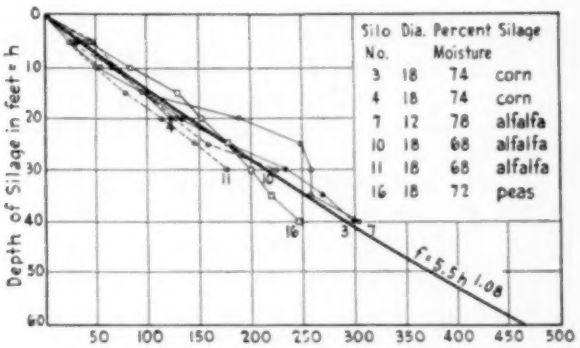

Fig. 3 — Vertical friction load in pounds per square foot = f

in which w = width of footing in inches at the base
h_1 = distance from top of silo to top of footing in feet
t = thickness of wall in inches
p = allowable soil pressure in psf

The increase in width of a footing for a 14x40 ft. silo when the weights of the roof, chute, reinforcing steel, footing and 2½ foot foundation wall were added to the weights of the stave wall and the vertical friction load, was 6.4 percent. Considering the uncertainty as to the allowable soil pressure, sufficient accuracy is obtained by use of the vertical friction pressure and the weight of the wall. If desired, the increment in width required for additional loads can be obtained by use of formula (5):

$$\Delta w = \frac{12\Delta W}{p\,\pi\,D} \qquad (5)$$

in which Δw = increment in width of annular ring footing for an increment in loads of ΔW pounds.
p = allowable soil pressure in pounds per square foot
D = diameter of silo in feet.

The widths of footings calculated by formula (4) for the recommended soil pressures are given in Table 1 and Table 2, with a 12 in. minimum width.

Wind loads need not be considered in the design of silos not exceeding 60 feet in height, because the vertical pressure due to wind is (a) small relative to the total load resulting from the gravity load of the silo and the vertical component of silage pressure, (b) of short duration when of

maximum intensity, and (c) because the chance of maximum wind load and maximum silage load occurring simultaneously is small.

The width of footing required for vertical load and wind load, if considered, should be calculated by formula (6):

$$w = \frac{12h_1}{p}(12.5l + 2.64h^{1.08}{}_1 + \frac{10h_2}{D}) \quad \ldots\ldots (6)$$

in which the significance of the symbols is as previously defined and

h_2 = distance from ground line to the top of the silo walls plus an allowance for the roof.

NOTE:—Formula (6) is based on a horizontal wind pressure of 15 psf on the vertical projection.

Plain or reinforced footings should be designed for depth according to Building Regulations for Reinforced Concrete (ACI 318-41) or the 1940 report of the Joint Committee submitting Recommended Practice and Standard Specifications for Concrete and Reinforced Concrete.

The depth of plain footings should be calculated by formula (7)

$$d = \frac{\sqrt{p}}{131} w \quad \ldots\ldots (7)$$

in which p = allowable soil pressure in psf.

and w = width of footings in inches as calculated from formula (4) or formula (6).

d = depth of footing in inches.

Shear is not a limiting factor in the design of silo footings as described herein.

Recommended soil pressures: In the absence of tests or other specific knowledge of the safe bearing capacity of the soil, it is recommended that the following values be not exceeded:

	Kind of Soil	Bearing Capacity psf	Ratio $\frac{d}{w}$
(Type 1)	Sand and gravel	8,000	.68
(Type 2)	Firm clay, wet sand or clay and sand mixture	4,000	.48
(Type 3)	Soft clay	2,000	.34

These values are used in calculating widths and depths of footings given in Table 2, with the help of formulas (4) and (7), 8 in. being the minimum depth.

Discussion of this report should reach the ACI Secretary in triplicate by April 1, 1944 for publication in the JOURNAL for June 1944.

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Discussion of Report of Committee 714:

Proposed Recommended Practice for the Construction of Concrete Farm Silos*

By WILLIAM W. GURNEY, DALTON G. MILLER and CHARLES G. SNYDER

By WILLIAM W. GURNEY†

For the benefit of those not very familiar with concrete silo construction but who are interested to know its details so that they may properly consider the Recommended Practice we are presenting, the following information may be helpful.

Concrete silos now constitute approximately 75 per cent of new silos constructed each year on America's farms. They are in three general classifications:

1) Concrete stave silos—built of factory made units whose most common measurements are 2½ in. thick, 10 to 12 in. wide and 30 in. long. There are also variations from the plain faced staves such as the ribbed stave which has a raised rib over the joint and the fluted stave which has a corrugated outer surface. Such staves are set vertically with a break of joint varying from 1½ to 15 in. Tiers of staves are hooped with steel which form the reinforcing for the structure. When the staves have been thus set to the desired height, the interior is given a seal coat of plaster of neat cement or cement sand mortar. This type of construction now leads all other types of silo construction by a large margin.

2) Monolithic concrete silos, built with forms at the place of construction with walls of 4- or 6-in. thickness with embedded reinforcing.

3) Concrete masonry silos, built with concrete masonry units laid in mortar with embedded reinforcing.

Here we have a circular structure with a relatively thin wall with a diameter ranging in most cases from 10 to 16 ft. raised to a height of 25 to 50 ft. This structure is filled with chopped forage which passes through

*ACI JOURNAL, Jan. 1944; *Proceedings* V. 40, p. 189. The report was presented March 2, 1944 to the 40th Annual Convention as information and for discussion.

†As chairman of Committee 714, Mr. Gurney made a statement Mar. 2, to the 40th Annual Convention as background information for ACI Membership in consideration of the report presented by reference only.

a heating or fermentation stage which in turn results in a moist, slightly acid ensilage which will remain in contact with the silo walls during the winter feeding period normally from September to May. The silo is exposed through this period to freezing and thawing.

These conditions produce a wear and tear on the structure which has caused the silo to be recognized as the hardest used structure on the farm. Coupled with this is the fact that silos must be built at relatively low cost in order to make them economically feasible for the farmer, the range being from about $350 for the smaller sizes to slightly more than $1000 for the largest.

There exists no standard recommended practice for the construction of concrete silos other than the American Concrete Institute's standard for concrete silo staves which sets a transverse breaking strength of 90 lb. per inch of width, no single stave falling below 75 lb. A maximum absorption of 6 per cent was also designated. This is a standard for concrete staves only and does not attempt to recommend a practice for general construction.

This standard was adopted in 1926 and no change of an official nature has been made since. Before Committee 714 was formed late in 1937, it had become apparent to the silo industries and to the agricultural departments of various colleges which had for various reasons become interested in the subject, that there existed a very real need for more exhaustive research, having in mind the development of a recommended practice for the construction of concrete silos.

The Portland Cement Association had long recognized this need and was led to a very early interest in the subject. To my personal knowledge they were experimenting with various silo coatings as far back as 1920. The now existing standard for concrete silo staves resulted from their early efforts.

Prof. D. G. Miller, Senior Drainage Engineer, Bureau of Agricultural Engineering, U. S. Department of Agriculture, stationed at the University of Minnesota, became interested in the subject as early as 1926. Professor Miller operated a testing laboratory at Minnesota originally for the purpose of studying the durability of drain tile in the alkali and acid soils of Minnesota. It was a natural step from concrete drain tile to concrete silos, both being in the agricultural field. This originally came to his attention because of widespread failures of concrete silos in Minnesota due to poor construction practices. By the time this committee was formed in 1937, Professor Miller had accumulated numerous data from tests he had made. Furthermore, he had become acquainted with most of the silo manufacturers of the Northwest and with the problems facing the industry.

The advent of grass silage which took hold first in the eastern part of the U. S. presented the problem of high moisture content in silage, causing leakage of excess moisture through the silo walls. Good corn silage normally has a moisture content of about 70 per cent. Good hay silage can also be made with 70 per cent moisture but unless prewilting is practiced the tendency is to make hay silage with much higher moisture content especially when a large amount of liquid preservative is added. Moisture content as high as 85 per cent sometimes results. Silage containing more than 75 per cent moisture produces a water pressure which causes leakage.

The New Jersey Agricultural Experiment Station at New Brunswich, N. J. became more silo conscious and began looking into this phase of the silo problem.

Associated with this work were: J. R. McCalmont, U. S. Dept. of Agriculture, H. E. Besley, W. L. Humphries, W. H. Tamm.

By 1937 it was deemed advisable to bring these various groups together in a committee of the American Concrete Institute. Largely through the efforts of J. C. Pearson, president of the ACI at that time, this was accomplished and Committee 714 was created late in 1937. This committee was charged with the preparation of a "Recommended Practice for the Construction of Concrete Silos."

This committee as finally formed consisted of the following 14 members.

Prof. J. W. Bartlett, Dairy Husbandry, New Jersey Experiment Station, New Brunswich, N. J.

D. G. Miller, Senior Drainage Engineer, Bureau of Agriculturel Engineering, U. S. Dept. of Agriculture, University of Minnesota.

Dr. Charles F. Rogers, Associate Biochemist, Ohio Agricultural Exp. Station, Wooster, Ohio.

Prof. Stanley Witzel, Farm Structures, University of Wisconsin.

J. W. Mc Calmont, Asst. Agricultural Engineer, Bureau of Agricultural Chemistry, and Engineering, U. S. Dept. of Agriculture, Washington, D. C.

H. B. Emerson, Lehigh Portland Cement Co., Chicago, Ill.

G. L. Lindsay, Universal Atlas Cement Co., New York, N. Y.

Walter Brassert, President, Concrete Silo Co., Bloomfield, Ind. (Wet cast and dry tamp staves)

Claude Douthett, Waterloo Construction Co., Waterloo, Ia. (Dry tamp staves)

R. A. Lawrence, Mason and Lawrence, Elgin, Ill. (Ribstone wet cast staves)

C. A. Mitchell, Portland Silo Co., Portland, Ind. (Wet cast staves)

B. M. Radcliffe, Interlocking Stave Silo Co., Wichita, Kan.

K. W. Paxton, Chief Engineer, Craine Inc., Norwich, N. Y. (Monolithic silos)

William W. Gurney, Madison Silo Co., Winona, Minn. (Dry tamp and monolithic silos)

After the usual amount of difficulty which is experienced in finding a chairman to head such a committee, Prof. C. A. Hughes, Structural Engineer, University of Minnesota, accepted the assignment. Professor Hughes prefaced his acceptance with the statement that he knew nothing about silos. However, Professor Hughes did know concrete. He was likewise a thorough and meticulous research man. He proceeded with an energetic program which started with a review of all the work that had previously been done. From this he branched into various laboratory tests and field experiments which covered a period of five years and resulted in a number of reports published in the ACI JOURNAL, the Journal of the American Society of Agricultural Engineers, and publication of American Society for Testing Materials, over that period. These reports are as follows:

"Factors which Influence the Durability of Concrete Stave Silos" by Dalton G. Miller, ACI JOURNAL, March-April 1938.

"Effect of Weight of Tampers and Number of Tamps on the Flexural Strength of Concrete Silo Staves," by C. A. Hughes, Dalton G. Miller, Philip W. Manson; ACI JOURNAL, Sept. 1938.

"Proposed Specifications and Methods of Testing for Concrete Staves to be used in Farm Silo Construction," By C. A. Hughes; ACI JOURNAL, Feb. 1940.

"Permeability, Acid and Absorption Tests of Mortars used in Dry-Tamped Silo Staves," by C. A. Hughes; ACI JOURNAL, June 1940.

"Observations on the Durability of Dry Tamped Silo Staves," by C. A. Hughes and Kenneth A. Anderson; ACI JOURNAL, Jan. 1942.

"Laboratory Tests of Concretes and Mortars Exposed to Weak Acids," by Dalton G. Miller, Philip W. Manson, Charles E. Rogers; presented before the Farm Structures Division at the Annual Meeting of the American Society of Agricultural Engineers at St. Paul, Minn. June 20, 1939.

"A Flow Method for the Determination of the Effects of Soluble Chemicals on Concrete," by Dalton G. Miller, Charles F. Rogers, Philip W. Manson; American Society for Testing Materials, 1939.

Professor Hughes coupled these experiments with a vast amount of field observation. He spent days visiting concrete silos of all ages which represented all the types of deterioration known to the industry.

These field observations were made with Mr. Miller and Mr. Manson, his assistant. A photographic folio composed of photographs of 100

silos showing inside and outside exposures was made. These silos were distributed throughout Minnesota and Wisconsin.

The result of all this work was a draft for a proposed Recommended Practice for the Construction of Concrete Farm Silos.

In June 1942 Professor Hughes, a Canadian citizen, joined the Canadian Army. Before leaving he prepared a final draft of Recommended Practice which was the third draft to be submitted to the committee for approval. This draft contained substantially the data as it now stands in the draft published in the ACI JOURNAL.

After Professor Hughes' departure, I was elected chairman to succeed him. My work has consisted entirely in taking the draft as left by Professor Hughes, and getting it into a form acceptable to the committee. In accomplishing this I am indebted to W. G. Kaiser of the Portland Cement Association and Harry Emerson of Lehigh Cement Company. It was then submitted to the ACI Standards Committee. Here again I am indebted to John R. Nichols, Boston, Mass. who contributed valuable work in re-editing and producing the published draft.

By DALTON G. MILLER and CHARLES G. SNYDER*

As a member of Committee 714 the senior author of this discussion voted to approve the "Proposed Recommended Practice for the Construction of Concrete Farm Silos" as published. There are, however, some provisions which we feel are not sound and which we believe should be modified before this Recommended Practice is adopted as a Standard.

First—We question the provisions on page 189 under *B. Footings* (1) which reads "*Depth below ground line:* The distance from the ground line to the base of the footings should be at least 2 feet in localities in which the ground freezes to a depth of 1 foot or more." Most silos are built and connected with the barn by a feeding floor which is usually covered. As a consequence, the ground on the side of the silo adjacent to the barn often times never freezes, nor is there much freezing immediately beneath a filled silo during a normal winter. On the other hand, that part of the foundation fartherest from the barn usually is in ground with a bare surface and subjected to just about the most severe conditions possible with respect to freezing. In Farmers' Bulletin No. 1869, "Foundations for Farm Buildings" issued in 1941 by the U. S. Department of Agriculture there are recorded in Table 1 the depths for placing bottoms of footings as recommended by various state agricultural colleges. For heavy permanent barns and storages the depths recommended for the states of Kansas, Illinois, Indiana, Iowa, Michigan, Minnesota, New Jersey, New York, Pennsylvania and Wisconsin range from 36 to 48

*Both of the Agricultural Experiment Station at University Farm, University of Minnesota, where Mr. Miller is stationed as Senior Drainage Engineer of the Soil Conservation Service, U. S. Dept. of Agriculture.

inches. In view of these facts it does not seem consistent for silo specifications to permit footings as shallow as 2 feet. We suggest that the paragraph in question be amended to read, "*Depth below ground line:* The distance from the ground line to the base of the footings should be at least 24 inches and should not be less than 36 inches in locations where the ground freezes to a depth of 2 feet or more."

Second—In the interest of clarity, we suggest that on page 192 the heading of Table 3 be amended to read, "Hoop Spacing for Concrete Stave Silos Designed for Silage with a Moisture Content not Exceeding 75 per cent." We also suggest that on page 193, paragraph (3) under section *E. Hoops*, be amended to read "The maximum hoop spacing for either grass or corn silage should be as given in Table 3. This table does not apply for silage with a moisture content above 75 per cent, as closer hoop spacing will be required for wetter silage."

Third—On page 194, under *4. Stave Silos*, we suggest that paragraph, (2) *Absorption*, be amended to read "The absorption after submersion in water for 10 minutes shall not exceed 3 per cent and shall not exceed 6 per cent after submersion in water for 24 hours." We have made many 10-minute absorption tests of silo staves extending over many years and are convinced that such a test indicates the degree of permeability of dry tamped staves much better than does the 24-hour test. However, when applied to wet cast staves the 10-minute absorption test is not always entirely satisfactory due to the smaller size of the pore spaces at the surfaces of the wet cast staves. This condition slows down the rate of initial penetration so much that the 24-hour absorption test is a better index of permeability of the whole section of wet-cast staves than is the 10-minute test. It therefore happens that fixing limits of absorption after soaking for 10 minutes and after soaking for 24 hours meets the test requirements for both dry-tamped and wet-cast silo staves. The limits of 3 per cent for the 10-minute soaking is about where it should be for a permissible 24 hour absorption of 6 per cent. Staves which meet the strength requirements of paragraph (1) under *4. Stave Silos* on page 194 of the Proposed Recommended Practice will have little difficulty meeting these two absorption limits. This is clearly shown in Table 15 of the paper, "Factors which Influence the Durability of Concrete Stave Silos," ACI JOURNAL, March-April 1938 *Proceedings* V. 34. Results reported in this paper were based on tests made at University Farm of the University of Minnesota of 1350 concrete silo staves.

Fourth—The one other comment we wish to make is in connection with Fig. 2 in the *Appendix* on page 200. Immediately below the figure, the statement is made: "The apparent accuracy with which the equation is expressed does not, of course, indicate that the formula will tell closely

the pressure in a given silo. It is evident from Fig. 2 that the lateral pressures for individual silos may vary widely from those given by the equation. A method of calculating silo pressures which includes the major variables, such as diameter and moisture content is highly desirable, but such a formula has not been developed, nor are the data required for its development available at the present time." Such being the case the practical value of the curve of Fig. 2 is just about negligible. On page 198, in the last paragraph, the statement is made "(a) that the relation between lateral pressure and head of silage is expressed by a curved line." Study of the various graphs of Fig. 2 reveals that such is not the case to the degree implied by the statement. Actually, the general pattern in nearly every case is for the pressures to plot as straight lines for the upper 20 or 25 feet of silage and from thereon to continue as straight lines, turning sometimes toward the ordinate and sometimes away from it. There could be several reasons for this which need not be discussed here except to say that, at best, the data of lateral pressures are extremely complex, ranging as they do for silages of moisture content of 64 to 81 per cent, for depths of fill from 20 to 40 feet, and for silos of diameters of 11.6 to 18 feet. We feel that there still remains reasonable doubt that the lateral pressure of silage increases as indicated by the formula of Fig. 2 which, it will be noted, does not conform to the behavior of fluids or so-called semi-fluids such as wheat. Of course, silage differs from a fluid or grain because silage is compressible and increases in unit weight with depth of fill, within limits. Consequently, it is conceivable that lateral pressures of silage could increase as indicated by the formula, to some undetermined depth, thereafter it may approach a straight line relationship or turn toward the ordinate.

In conclusion, we have a feeling that, from a practical standpoint, the dividing line between low moisture and high moisture silage is not 75 per cent but is perhaps around 70 or 71 per cent. If no consideration is to be given silo diameters, we believe the Hughes formula is satisfactory for low moisture silage, but gives results too low for silage of high moisture content. How much too low is difficult to say but we would want to use considerably more steel if the silage were to run around 80 per cent moisture. Actually, for all practical purposes, 11 lb. per sq. ft. per foot of depth for silage with a moisture content around 70 to 71 per cent and 20 pounds for high moisture content silage probably is not so very far wrong for 14-foot silos provided the design stress of the steel is assumed as 18,000 psi. Using values of 11 and 20 lb. pressure it would be unwise to jump the design strength of the steel to 20,000 psi.

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Accelerated Tests of Concrete Expansion Due to Alkali-Aggregate Reaction*

By ROY W. CARLSON†
Member American Concrete Institute

SYNOPSIS

Reports length changes up to 2 years in mortars containing 22 different aggregates. Shows the accelerating effects of sodium hydroxide added to the mixing water and of storage temperatures of 110 F and 150 F. Although it appears that the main effect of the higher temperatures is to hasten the expansion due to reactive aggregates, it remains to be proved whether some aggregates such as quartz, which cause expansion at the higher temperatures, will ever cause expansion at 70 F or less.

Among the aggregates tested, all those containing silica caused some expansion at the higher temperature, and conversely aggregates lacking in silica caused no expansion. Greatest expansion of 2 percent in length was caused by only 5 percent of an aggregate containing opaline silica blended with 95 percent of a non-reactive aggregate.

INTRODUCTION

When T. E. Stanton disclosed in 1940 the large concrete expansions which occurred with certain reactive aggregates, the question was raised as to whether other aggregates were reactive also. The conditions under which expansion occurred were so exceptional that some reactive aggregates might exhibit no expansion in concrete and therefore be fully satisfactory for the conditions of use, while in a few cases imperfect performance might result without being attributed to the reactive aggregate. As is well known now, the large expansion seems to occur only (1) after months or years, (2) when the aggregate is reactive, (3) when a high-alkali cement is used, and (4) when the concrete is maintained neither fully wet nor dry. Only when all four of these conditions prevail is expansion likely to occur. As a result of current tests, a fifth condition might be imposed for aggregates of lesser reactivity, this condition being that the concrete expands only if it is kept warm as well.

In view of the slowness of the expansion due to alkali-aggregate reaction, and of the uncertainty about many siliceous aggregates, it

*Received by the Institute, Nov. 19, 1943.
†Research Engineer, University of California.

appeared desirable to learn as soon as practicable which common minerals might cause expansion under conditions likely to be encountered, and whether reliance could be placed on results obtained under accelerating conditions. For test purposes, the principal accelerating conditions were believed to be: 1) elevated temperature, 2) alkali added to mix, 3) rich, mortar mix, and 4) aggregate size limited between about No. 48 and No. 4 sieves. Consequently, exploratory tests were begun in 1940 in Massachusetts Institute of Technology laboratories on about 30 various aggregates. The more significant tests are reported here.

DETAILS OF TESTS

All aggregates being investigated were prepared to pass a No. 4 sieve and be retained on a No. 48 sieve, since Stanton had shown the finer sizes to cause less expansion. In order to avoid abnormal mixes, all aggregates were adjusted to a fineness modulus of 3.2 by adding the needed amount of limestone fines passing the No. 100 sieve; these fines were assumed to be non-reactive and later proved to be so. An arbitrary mix was used of 1:2 by weight (including the limestone fines as aggregate), and the water cement ratio was 0.47 throughout. For the main tests two different mixes were employed, one of them containing a high-alkali cement and the other containing the high alkali cement with 0.5 percent of Na_2O added as $NaOH$ to the mixing water. Low-alkali cements were used as controls in a few cases only for very long-time tests. Three storage temperatures were adopted arbitrarily, 70 F., 110 F., 150 F. The specimens were small bars, 1½ by 1½ by 6 in., with stainless steel inserts at the ends for length measurement with a dial-type extensometer. The moisture was maintained in and around the specimens by placing each group of 6 bars on a grid shelf in an air-tight gallon can with a shallow layer of water in the bottom of the can but not touching the shelf or bars. All specimens were left in the molds one day at about 75 F.; initial readings were then taken and specimens placed in metal cans for continued storage at the respective temperatures.

A brief description of the various aggregates is continued in Table 1. It may be noted that a number of practically pure minerals were included. The particular dilution of an aggregate producing greatest expansion appeared to have been missed for several of the most reactive aggregates, particularly siliceous magnesian limestone, and possibly for muscovite mica. The siliceous magnesian limestone was used at 5 percent only, the remainder being siliceous sand from Long Island Sound (shown later by separate tests to be slightly reactive at elevated temperatures). Stanton has shown 20 percent of this material to be the the worst amount. The Muscovite mica also was used at 5 percent only, it also being diluted

with the siliceous sand from Long Island Sound; there is little evidence as yet regarding the worst percentage of the mica.

DISCUSSION OF TEST RESULTS

The mortar expansions observed with most of the aggregates are shown in Fig. 1, 2 and 3; the remainder being described by mere state ments in Table 1. In all cases, the broken lines refer to specimens containing 0.5 percent of added sodium oxide (as *NaOH*). The solid lines refer to specimens containing identical cement, which had more than one percent of the combined oxides of sodium and potassium, but with no alkalies added to the mixing water.

Referring to the figures and to Table 1, it may be noted that all normal weight aggregates containing silica caused some mortar expansion, although in many cases the expansion was little or nothing at 70 F. up to the latest age shown of more than 2 years. On the other hand, aggregates containing no silica caused no expansion. Greatest expansion was caused by 5 percent of San Pedro shale blended with 95 percent of Long Island sand. This expansion was 2 percent of the length or about 6 percent of the volume of the mortar and the maximum expansion occurred at 70 F. The San Pedro shale contained what is called "opaline" silica, as did the Piru shale, and the Siliceous Magnesian Limestone. It is probable that equally large expansions would have been observed with these materials had the worst percentage been used.

Although the elevated temperature appears merely to hasten the expansion of the mortar, it remains to be proved whether some siliceous materials like quartz and graywacke will ever cause expansion at 70 F. And if such materials do cause expansion under the long-continued moist storage at 70 F.; they would only be expected to cause expansion in structures at that temperature where the other conditions are such as to preserve both the alkalies and the needed degree of moisture continually within the concrete. Observations are being continued on the specimens which showed expansions at elevated temperatures but little or no expansion at 70 F.

The effect of adding sodium hydroxide to the mixing water is generally to produce quicker and larger expansions. But the effect is not fully consistent. For example, the added alkali reduced the expansion where siliceous magnesian limestone was the aggregate, while in the case of quartz the added alkali caused a surprisingly large expansion at 150 F. only. An explanation is necessary in the latter case, however, because for some unintended reason the moisture was lost for a time from the can holding the quartz specimens at 150 F. After restoring the moisture in the can at the age of 10 months without wetting the specimens, the specimens containing added alkali began to grow dis-

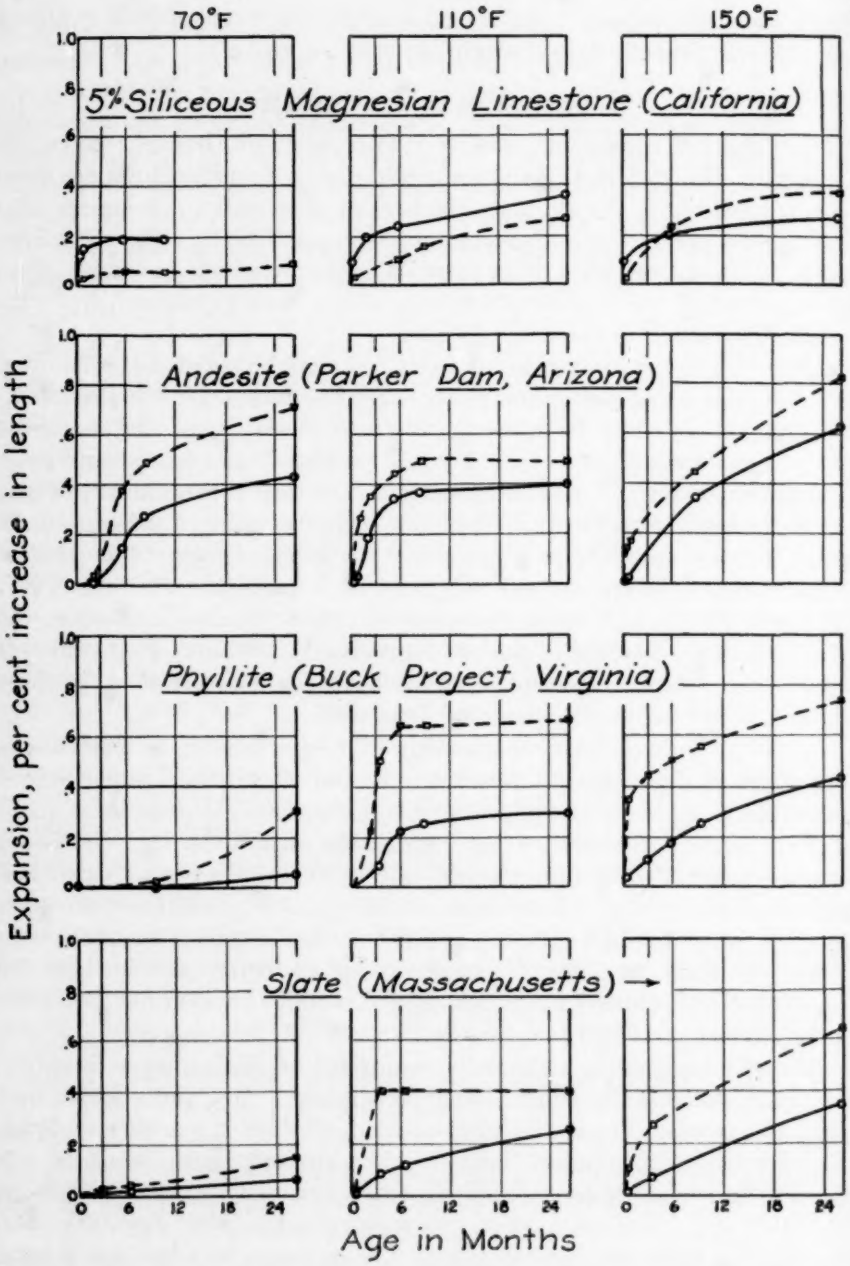

Fig. 1—Observed expansion of mortars containing aggregates 1, 16, 21, and 22. Solid lines refer to mortars containing high-alkali cement without addition; dashed lines same cement but with 0.5 percent Na_2O added, by weight of cement.

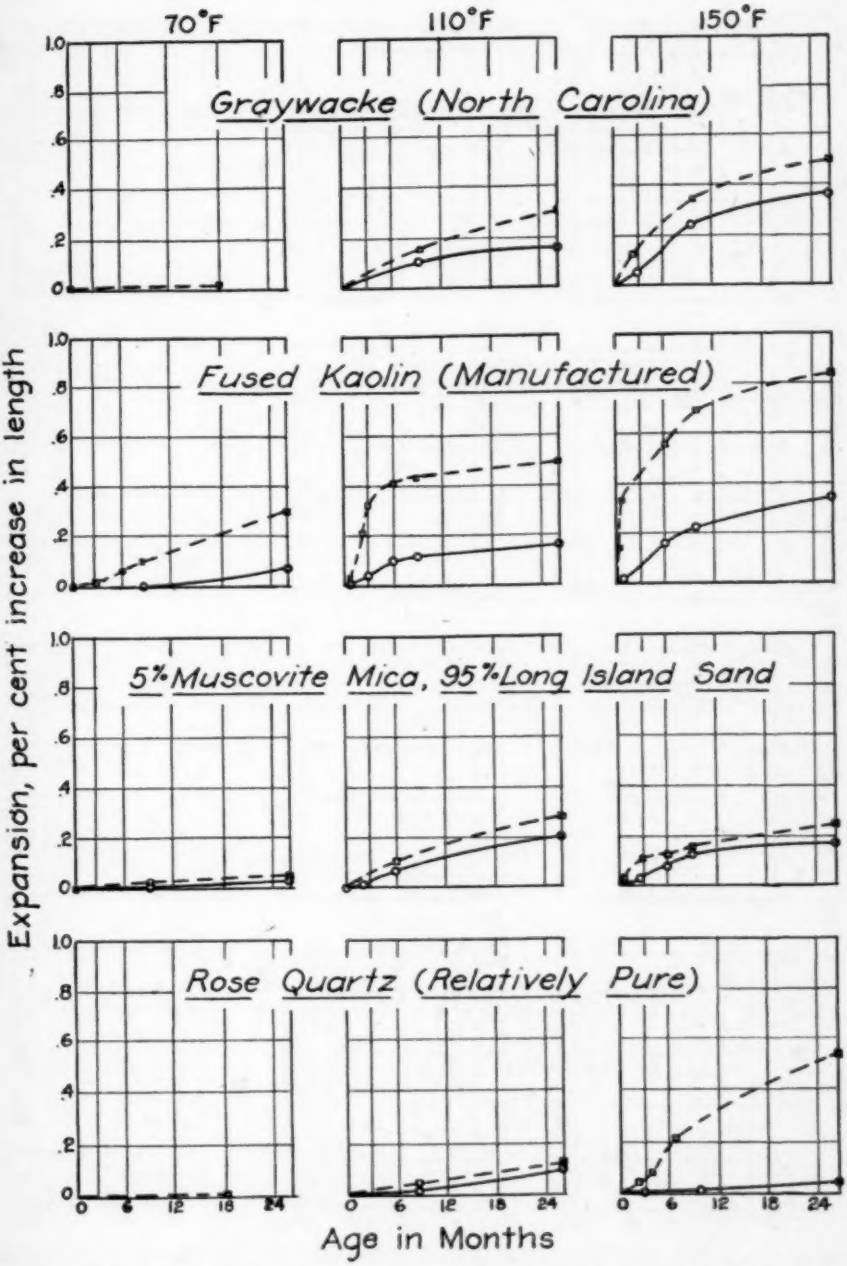

Fig. 2—Observed expansions of mortars containing aggregates 7, 11, 15, and 18. Solid lines refer to mortars containing high-alkali cement without addition; dashed lines same cement but with 0.5 percent Na_2O added, by weight of cement.

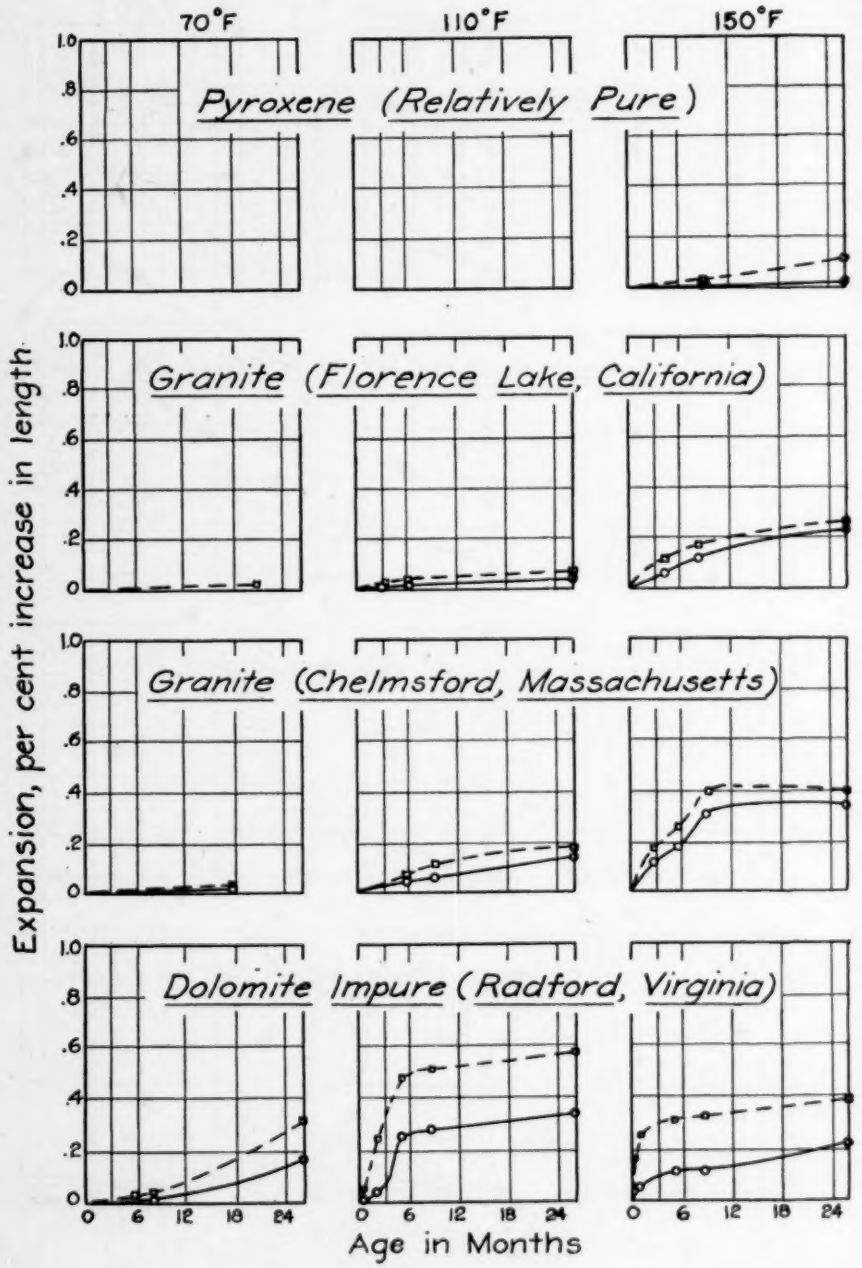

Fig. 3—Observed expansions of mortars containing aggregates 4, 8, 10, and 17. Solid lines refer to mortars containing high-alkali cement without addition; dashed lines same cement but with 0.5 percent Na_2O added, by weight of cement.

TABLE 1—BRIEF DESCRIPTION OF AGGREGATES TESTED FOR MORTAR EXPANSION

Aggregate	*Description*	*Expansion of Mortar*
1. Andesite	Hand-picked andesite from Parker Dam; used 100%, as compared with only a few percent occurring in Parker aggregate.	See Fig. 1.
2. Blast Furnace Slag	Details of composition not available.	Slight expansion at 150F only.
3. Corundum	Pure aluminum oxide.	No expansion.
4. Dolomite, Virginia	Impure dolomite containing from 5 to 10 percent of silica.	See Fig. 3.
5. Feldspar (albite)	Pure soda-feldspar mineral.	Slight expansion at 150F only.
6. Feldspar (orthoclase)	Pure potash-feldspar mineral.	Slight expansion at 150° only.
7. Fused Kaolin	An artificial stone produced by fusing kaolin clay into hard clinker consisting of mullite grains with silica-glass matrix.	See Fig. 2.
8. Granite, California	From High Sierras, Florence Lake.	See Fig. 3.
9. Granite, weathered	Same as "8" but weathered for 15 years after being crushed to make aggregate.	Approx. same as 8.
10. Granite, Mass.	Very hard, dense granite from granite-block quarry, contained muscovite mica.	See Fig. 3
11. Graywacke, N. Carolina	A fine-grained gaywacke.	See Fig. 2.
12. Haydite, St. Louis	Normal product as used for concrete ships.	No expansion to 12 months.
13. Hornblende	Practically pure mineral containing normal amount of combined silica.	Slight expansion at 150F only.
14. Limestone, pure	Practically pure calcium carbonate.	No expansion.
15. Mica, Muscovite	Practically pure muscovite between No. 48 and 28 sieves, 5% of which was blended with 95% of Long Island sand.	See Fig. 2.
16. Phyllite, Virginia	Aggregate used for Buck Project.	See Fig. 1.
17. Pyroxene	Practically pure pyroxene of augite group, containing normal amount of silica in combination.	See Fig. 3.
18. Quartz, "Rose"	Practically pure silica	See Fig. 2.
19. Shale, Peru	A California shale containing opaline silica.	5% of the shale caused large expansions under all conditions, 20% caused very little expansion.
20. Shale, San Pedro	Another California shale containing opaline silica.	5% of the shale caused expansions as great as 2% of length at 70F. and 110F. but less at 150F. 20% of the shale caused slight expansion.
21. Sil. Mag. Limestone	California aggregate reported by T. E. Stanton and containing opaline silica, 5% blended with 95% of Long Island sand.	See Fig. 1. Note: Worst percentage about 20.
22. Slate, Mass.	Hand-picked from a Boston glacial-gravel aggregate.	See Fig. 1.

proportionately. This seems to indicate that there may be a certain intermediate moisture condition (probably governing the concentration of alkalies in solution), which is much worse than the arbitrary moisture content due to retaining the original mixing water.

Spots appeared on all specimens showing even moderate expansion, but not on specimens which did not expand. The spots differed widely in shade, some being nearly white and others being nearly black.

Perhaps the most consistent behavior was evidenced by specimens containing the artificial aggregate known as "fused kaolin". A reference to Fig. 2 shows that the mortar expansion was increased consistently with higher temperature and with added alkali. Note that the times required to reach an expansion of 0.1 percent without added alkali were respectively about 3 months, 6 months and more than 2 years for the temperatures of 150, 110, and 70 F. With added alkali, the corresponding times were 2 weeks, 6 weeks, and 32 weeks. With the fused kaolin the effect of added alkali was unusually large.

Low-alkali cements produced little or no expansion at any temperature with mildly reactive aggregates, at least up to the age of 2 years. The impure dolomite, for example, was tested with five other cements besides those for which results are shown in Fig. 3. These other cements had total alkali contents ($Na_2O + K_2O$) of 0.36, 0.46, 0.62, 0.75, and 1.15 percent. Only the two highest alkali contents produced appreciable expansion in the two years of observations to date, even at elevated temperatures. If it is granted that the combined accelerating effects of the elevated temperature, the mortar mix, and the selected sizes amounts to even as much as 10 times normal rate, then the low-alkali cements would insure proof against alkali-aggregate expansion for at least 20 years. For the particular purpose of preventing serious expansion where mildly reactive aggregates must be used, therefore, the restriction of the amount of the oxides of sodium and potassium in the cement seems to be desirable. This conclusion must remain tentative until such time as continued tests provide a sound basis for an ultimate decision as to the best corrective measures. The significance of the accelerated tests on mildly reactive aggregates should become more clear when, in addition to continued tests, a number of corresponding structures have been observed over long periods. Observations will continue on several structures containing aggregates reported here.

ACKNOWLEDGMENT

Credit is due to F. J. Mehringer of the Massachusetts Institute of Technology for his careful work in preparing and observing specimens.

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Vol. 15 No. 6 7400 SECOND BOULEVARD, DETROIT 2, MICHIGAN June 1944

Discussion of a Paper by Roy W. Carlson:

Accelerated Tests of Concrete Expansion Due to Alkali-Aggregate Reaction*

By THOMAS E. STANTON†

While it is true that, as reported by Carlson, California has found certain sizes of fine aggregate more reactive than others, our investigations indicate the 30 to 80 mesh size apparently to be the most reactive. The data on which this statement is based were originally shown in Fig. 6, page 66, Transactions of the American Society of Civil Engineers, V. 107 (1942). This figure shows the data up to 6 months only. Subsequent measurements on the same specimen show the following results at 48 months.

Size of Particles of Reactive Admixture	—80	80 — 30	30 — 10	10 — 3
Per cent Exp. in 48 months...	.003	.810	.552	.536
Sonic E. x 10^{-6}	4.27	2.58	3.10	2.41
M. R. psi	1297	567	581	466

Five per cent of 80-30 mesh siliceous magnesian limestone (No. 28039) was substituted for an equivalent percentage of the neutral Russian river sand in a 1:2 mortar mix. All of the bars (1 x 1 x 10 in.) were tested for sonic *E* and then broken as beams at 48 months with the results shown. Recent California practice has been to use the 80 to 20 mesh fraction for investigative and control tests and either 10 per cent of the siliceous magnesian limestone No. 28039 or 2½ per centto 3 per cent of the opaline chert No. 28038.

Carlson describes tests with a number of aggregates in which 0.5 per cent of sodium oxide (as *NaOH*) was added to the mixing water. In

*ACI JOURNAL, Jan. 1944; *Proceedings* V. 40, p. 205.
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Fig. 1, 2 and 3 he shows that the *NaOH* definitely accelerated the expansive reactions in all cases, except at 70 and 110 F. with 5 per cent siliceous magnesian limestone (California).

Our experience checks Carlson's findings. Studies were started over two years ago on representative sands from all sections of the state to ascertain which, if any, possessed adverse reactive properties similar to those encountered with the opaline cherts in the coast aggregates from Monterecy to Los Angeles.

Tests were made on 1:2 mortar mixes at 70 and 130 F. with and without one per cent *NaOH* added to a high-alkali cement (1.07 per cent alkali).

The averages of the tests at 12 months on forty-five normally unreactive sands from all sections of the State were as follows:

	Without *NaOH*		1 Per cent *NaOH*	
Storage temperature	70°F.	130°F.	70°F.	130°F.
Per cent expansion	.019	.067	.064	.146

Some acceleration due to temperature and some to the *NaOH* can be noted, but even in the case of the 1 per cent *NaOH* admixture at 70 F. the expansion was moderate.

On the other hand, thirteen definitely or potentially reactive fine aggregate-high alkali cement mortars reacted as follows:

Series No.	Aggregate	Per cent Expansion at 12 Months			
		Without *NaOH*		1.0 Per cent *NaOH* added to Cement	
		70°F.	130°F.	70°F.	130°F.
28074	Saticoy Sand	.346	.493	.354	.426
28074A	Saticoy "	.338	.498	.286	.356
28080	Truckee R. (Reno) Sd.	.035	.463	.324	.569
28102	San Joaquin R. Sand	.046	.173	.056	.118
28104	R. R. + 2.5 per cent No. 28038	1.193	1.547	.569	.572
28104A	R. R. + 2.5 per cent No. 28038	1.438	1.209	.513	.283
28105	R. R. + 10.0 per cent No. 28039	.898	.282	.457	.777
28106A	R. R. + 10.0 per cent No. 28039	.998	.635	.287	.253
28107A	R. R. + 2:5 per cent No. 28038	1.556	0.978	.459	.369
28107B	R. R. + 5:0 per cent No. 28038	1.046	1.397	.962	.717
28107C	R. R. + 10:0 per cent No. 28038	.050	—.004	1.266	.290
28110	Sidebotham Sand	.246	.354	.170	.222
28116	Cowlitz Sand (Wash.)	.154	.126	.489	.382

This group of test data was compiled from several test series extending over a considerable period. Some of the tests were made to determine reproducibility and others to determine the effect of increasing percentages of the reactive minerals.

Attention is called to the 28107 Series showing the extent to which the expansions at normal temperatures without the *NaOH* addition to the cement fell off as the percentage of the reactive chert (No. 28038 was increased from 2.5 to 10 per cent of the fine aggregate content. Note that with 10 per cent No. 28038 the expansion was negligible at either 70 or 140 F. without sodium hydroxide, but that with 1 per cent *NaOH* added by weight of the cement, the expansion at 70 F. equaled 1.266 per cent in 12 months but at 130 F. was only 0.290 per cent. On the other hand with the most highly reactive combination containing 2.5 per cent No. 28038, the highest expansion occurred at the normal temperature of 70 F. and without the sodium hydroxide addition.

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Studies Relating to the Mechanism by Which the Alkali-Aggregate Reaction Produces Expansion in Concrete*

By W. C. HANSEN†

SYNOPSIS

The expansion and cracking of certain concrete structures have been attributed to a reaction between the aggregate and the alkali hydroxides produced by the hydration of the cement minerals. An hypothesis of the mechanism by which this reaction produces expansions in concrete is given. This hypothesis is based on the reaction of alkali hydroxides with opaline silica in the aggregate producing alkali silicates which because of the semi-permeable nature of the hardened cement-paste give rise to osmotic pressures. Several lines of evidence support this hypothesis, and the hypothesis appears to explain satisfactorily why opaline silica does not produce abnormal expansions through reaction with calcium hydroxide.

INTRODUCTION

T. E. Stanton, from studies [1][2]‡ published in 1940, concluded that a reaction between certain components of aggregates and the alkali hydroxides released by the portland cement minerals during hydration was the cause of the expansion and cracking of some concrete structures in California. This conclusion opened up a new line of investigation, and several papers‡ have been published in discussion of Stanton's papers and in the presentation of evidence of damage from an alkali-aggregate reaction in other structures.

A number of laboratories are now engaged in research designed to provide answers to the many questions which have been raised by Stanton's disclosure. One question under study is the mechanism by which a reaction between an alkali hydroxide and some component of an aggregate could produce the expansion and cracking attributed to it.

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‡See bibliography at end of text.

In the studies carried out in the Research Laboratory of the Portland Cement Association, a number of observations have been made which seem to provide an insight into this mechanism. These observations and an hypothesis based upon them are presented in this paper, in the hope that they will be of assistance in the solution of the problems now confronting the research worker in this field.

REACTION OF OPALINE SILICA WITH ALKALI HYDROXIDES

At the present time, opaline silica is known to be common to a number of aggregates which have produced excessive expansions in mortars and concretes. In such expanded concrete, it is always possible to find a jelly-like material which Stanton [2] called a gel. Stanton gives the partial oxide compositions of two samples of gel, which show that they contain various materials, but consist largely of silica, alkali oxides and water. It is, of course, extremely difficult to remove these gels from the concrete without contaminating them with other components of the aggregate and with the hardened cement paste. For this reason, such analyses can be used only as qualitative evidence of the compositions of the gels. However, from the analyses given by Stanton and by others, there seems to be no reason to doubt that the gels contain appreciable quantities of alkali silicates and that these were produced in the concrete by a reaction between silica and alkali hydroxides. This reaction probably is one of the well-known reactions of silica with alkali hydroxides such as those shown in equations (1) and (2) for *NaOH:*

$$4SiO_2 + 2NaOH = Na_2Si_4O_9 + H_2O \quad \ldots\ldots (1)$$

$$SiO_2 + 2NaOH = Na_2SiO_3 + H_2O \quad \ldots\ldots (2)$$

REACTION OF SILICA-GEL WITH ALKALI HYDROXIDES

Quartz has been used extensively as a concrete aggregate without ever having shown any evidence of reacting sufficiently with any component of the cement paste to produce any deleterious effects in concrete. Therefore, if other forms of silica such as opaline silica are capable of producing such effects in concrete, the physical properties and possibly the degree of hydration of the silica must be of paramount importance unless there are associated with the silica, in certain aggregates, materials which catalyze the reaction of the silica with the alkali hydroxides. To determine whether or not pure silica reacts with alkali hydroxides in hardened cement-pastes, a few studies were made in which silica-gel was used as a component of the sand in mortar prisms.

The silica-gel used in these studies was the commercial product prepared by igniting a very pure precipitated silica. It is a highly absorbent material consisting of extremely fine particles of silica.

This crushed silica-gel, graded 16-6 mesh, was used to replace a part of the Elgin sand in 1-2 mortars, by weight, which were made into 1x1x11¼-in. prisms. The prisms were stored upright in covered containers in water to a depth of about 1 in. After 4 mo. storage a prism made with a cement containing 1.00 percent Na_2O and 0.08 percent K_2O and with 1 percent of silica-gel in the sand was broken and examined under low magnification. The silica-gel particles were clearly visible and outwardly appeared to be unaltered. However, when these particles were probed with a needle, it was found that many of the particles had been converted to a soft transparent jelly-like material. This material was observed to dissolve rapidly when a drop was placed in water on a slide and viewed under low magnification, which demonstrated that the hard water-insoluble silica-gel had been converted to a soft water-soluble product during this period of contact with the hardened cement-paste and that a catalyst was not required for this reaction.

Since a catalyst is not required for this reaction with silica-gel, it is interesting to compare the reactivity of different forms of silica with alkali hydroxides. Table 1, taken from "The Properties of Silica," by Robert S. Sosman (Chemical Catalog Co., page 81) gives a relative measure of the rate of solution of various forms of silica in a solution of KOH. The first material listed in this table probably corresponded closely to the silica-gel used in this study.

TABLE 1—DISSOLVING-RATE OF SILICA IN NORMAL KOH SOLUTION AT BOILING POINT (WINKLER, 1878)

Form or Variety	Source	Time	Percent Dissolved
Micro-amorphous-dehydrated	Made from water glass	1 min.	100.0
Opal, dehydrated	Borsoe, Hungary	1 hr.	89.1
Hyalite, dehydrated	Walsch, Bohemia	1 hr.	56.1
Tridymite	Siebenbürgen	1 hr.	49.6
Asmanite (tridymite)	Rittersgrün Meteorite	1 hr.	43.9
Micro-amorphous (dehydrated)	Made from SiF_4 & H_2O	1 hr.	23.4
Quartz		1 hr.	5.1

It is seen from these data that quartz is markedly more resistant to boiling KOH solutions than are the other forms of silica studied. It is, therefore, readily understandable that the rate of reaction of quartz in a cement-paste might be too slow to produce any measurable effect over a period of years, whereas the rates of reaction of silica-gel and opaline silica might be sufficiently rapid to be measurable within a few months.

EXPANSIVE REACTIONS

Concrete technologists are familiar with the expansions produced by hard-burned lime and magnesia when these materials hydrate in concrete in accordance with equations (3) and (4).

$$CaO + H_2O = Ca(OH)_2 \quad (3)$$

$$MgO + H_2O = Mg(OH)_2 \quad (4)$$

L. S. Brown and M. A. Swayze [13] show by means of microphotographs the results of the hydration of CaO and MgO in concrete. It is evident from these microphotographs that during the hydration the $Ca(OH)_2$ and $Mg(OH)_2$ do not migrate from the site of their formation. That is, it appears that the CaO and MgO change directly from the solid oxides to the solid hydrates. If this occurs, the concrete must either yield or crack because a given weight of either oxide occupies less volume than does the corresponding hydrate produced from this weight of oxide. Dr. Brown in private communications has advanced this explanation for the cracking of concrete by the hydration of CaO and MgO.

Theoretically it seems entirely possible that CaO and MgO could hydrate directly to solids in a hardened cement-paste. This paste has the properties of a porous solid in that it gains and loses water depending upon the humidity of the environment and in that ions and molecules can diffuse through it. When a particle of CaO is embedded in the hardened paste, the CaO may be visualized as being tightly enclosed in a fine-meshed screen the pores of which are filled with a solution saturated with $Ca(OH)_2$. Since the solution is saturated with respect to $Ca(OH)_2$, there is no tendency to dissolve more $Ca(OH)_2$, but CaO is unstable in this solution and tends to hydrate. If the CaO dissolved in this solution, where it came in contact with the solution in the paste, it should precipitate immediately as the hydrate. Moreover, it seems entirely possible that the CaO might combine with the water from this solution to form the hydrate without first going into solution. Also it is known that CaO and MgO will hydrate in the absence of liquid water by combining with moisture from the air. If CaO and MgO embedded in the cement-paste hydrated by either of the last two mechanisms, they would be converted directly from one solid phase to another solid phase and would have no opportunity to migrate from the site of formation.

Considering now the reaction of SiO_2 with alkali hydroxides, the particle of SiO_2 may be visualized as being enclosed in a fine-meshed screen the pores of which are filled with a solution of the alkali hydroxides. Silica differs from CaO and MgO in that CaO and MgO can hydrate in moist air in the absence of liquid water, whereas, for SiO_2 to react with alkali hydroxides, a solution phase is necessary. The case of SiO_2 also

differs from that of CaO and MgO in that the solution in the cement-paste is not saturated with the alkali silicates and in that the alkali silicates are relatively soluble materials, whereas in the case of CaO and MgO the solutions in the pastes are saturated with the respective hydrates and these hydrates are relatively insoluble. When the SiO_2 reacts with the alkali hydroxides in the solution in the cement-paste, the alkali silicates would be expected, because of their solubility, to diffuse into this solution away from the site of formation. Observations indicate that this is probably not the case, but if this did occur and the alkali silicate precipitated in the paste, no expansions would result from the reactions of SiO_2 and alkali hydroxides because the alkali silicates undoubtedly require less volume than that originally occupied by the SiO_2 and alkali hydroxides which formed them.* Therefore, it does not seem possible to account for the expansion produced by this reaction by the same mechanism as that which produces expansion when CaO and MgO hydrate in a cement paste. Accordingly some other mechanism seems to be required.

During the examination of the broken faces of pieces of mortar from a specimen which had expanded because of the alkali-aggregate reaction, an observation was made which led to the studies described later and to the explanation offered below for the mechanism by which this reaction produces expansions in concrete. In this examination a pocket of viscous liquid was found in a piece of the mortar which had never been immersed in water; hence there was no possibility that the liquid had entered through a crack in the specimen. To account for the presence of this liquid in the mortar, it is necessary to consider the properties of alkali-silicates.

It seems to be well established that the silicate ions in solutions of alkali silicates tend to associate into complex ions. Accordingly, these ions might not be capable of diffusing through the hardened cement-paste. If this were the case, the cement-paste would act as a semi-permeable membrane toward the silicate ions. That is, the membrane would permit water and the ions and molecules of the alkali hydroxides to diffuse through it, but it would not permit the diffusion of the silicate ions. These are the requirements of an osmotic pressure cell. Under these conditions any alkali silicate formed on the surface of an aggregate particle would tend to draw solution from the cement-paste and form a

*The densities of many of the alkali silicates are not known, but the density of $K_2Si_4O_9.H_2O$ is given as 2.417 in Vol. I of the International Critical Tables. In the same volume the density of opal is given as 2.1 to 2.3 and that of KOH as 2.044. Using the value of 2.3 for opal, calculations show that in the reaction $2KOH + 4SiO_2 = K_2Si_4O_9.H_2O$, the reactants occupy a volume of 159.3 as compared to a volume of 145.8 for the potassium silicate. The volume of the reactants is 169.3 if the value of 2.1 is used for opal. Similar small contractions in volume would be expected in the formation of other hydrated alkali silicates from opal and alkali hydroxides.

pocket of liquid within the specimen which would exert hydrostatic pressure against the confining paste.

Since the alkali-silicates must form in the space originally occupied by the silica from which they were formed, and since these silicates must occupy a greater volume than that occupied by the silica alone, they would tend to exert pressure against the confining paste which would be augmented by the hydrostatic pressure. The tendency of the alkali-silicates to draw solution into this space would also tend to accelerate the reactions and accordingly the development of pressure because the solution would carry additional alkali hydroxides to the SiO_2 particle.

If the hardened cement-paste is impermeable to alkali silicates, it is possible to compare the mechanisms by which CaO, MgO and SiO_2 may produce expansions in concrete. Such a comparison shows that the mechanisms are similar for the three oxides in that the cement-paste attempts to confine the reaction products to the space originally occupied by the oxides. It also shows that the mechanisms differ in that in the case of CaO and MgO the reaction products are solids, whereas for SiO_2 the reaction products tend to be dilute solutions.

EVIDENCE SUPPORTING THE OSMOTIC PRESSURE HYPOTHESIS

The mechanism just outlined for the expansion of concrete through the reaction of SiO_2 with alkali hydroxides in solution was arrived at from the observation of a pocket of liquid in an expanded specimen and from the known properties of alkali silicates. A number of lines of evidence which support this hypothesis are given below:

A. In order to demonstrate the possibility of hardened cement-paste acting as a semi-permeable membrane toward sodium silicate, a thimble was prepared from neat cement-paste. This thimble filled with a solution of sodium silicate and tightly stoppered with a rubber stopper through which a glass tube extended was immersed in a bottle of distilled water. The liquid, which in the glass tube was level with the water in the bottle at the start, gradually rose until it stood several inches above the original height. It should be pointed out that this experiment and the observations discussed later do not show that the hardened cement paste is completely impermeable to the alkali silicates, but they do show that the hardened pastes are sufficiently impermeable to permit the development of hydrostatic pressures.

B. As pointed out above, if this mechanism operated in mortars and concretes, pockets of alkali silicate solutions should exist in specimens which had expanded because of this reaction. The fractured faces of a number of such specimens have been examined under low magnification.

Pockets of liquids of varying viscosities have been found in many of them. The viscosity of the liquid increases on exposure to air until the liquid changes to a transparent solid. The viscous nature of these liquids and their solidification to transparent solids supports the conclusion that they are solutions of alkali silicates.

When these liquids solidify on the fractured surface, they impart a glazed appearance to that surface. Such glazed areas have been observed in many specimens in which it was not possible to detect actual liquid.

C. In the cases of the phyllite in the concrete of Buck Falls Dam and the andesitic and rhyolitic gravels in the concrete of Parker Dam, attention has been called by various writers to the borders or "rims" on some of the aggregates, some of which they believe developed after the aggregates were incorporated in the concrete. Investigators are not certain whether such "rims" have been produced by a reaction of the cement with the aggregate or whether they are simply the result of infiltration of the alkali silicates into the pores of the aggregate. It is somewhat difficult to visualize an appreciable penetration of a gelatinous material into an aggregate, but it is easy to visualize the penetration of an alkali silicate sclution. Such a solution, when the aggregate is dried, would be converted to transparent amorphous silicates in the pores of the aggregate. These silicates undoubtedly would change the appearance of the aggregate, but because of their amorphous condition, they would be difficult to identify by petrographic examination. These "rims" might therefore be evidence of the existence of silicate solutions in these concretes during some period of their life.

D. A fact reported by others and observed in this laboratory is that the jelly-like material found in these expanded concretes often occurs both as a white opaque material and as a clear transparent material. It is known that calcium salts react with alkali-silicate solutions and produce solid white calcium silicates as illustrated by equation (5) below.

$$Na_2SiO_3 + Ca(OH)_2 = Ca_2SiO_3 + 2NaOH \quad \ldots\ldots\ldots\ldots\ldots (5)$$

It appears, therefore, that the white opaque material probably is a calcium silicate formed by a reaction of the alkali silicate with the calcium hydroxide, which is always present to some extent in solutions in contact with hardened cement-pastes, and that the transparent product is the hardened alkali silicate. It would be expected that because of the presence of calcium hydroxide in the solution in the hardened cement-paste it would be impossible to obtain a sample of these reaction products uncontaminated with lime. Also, the reaction illustrated in equation (5) would tend to convert the alkali silicate solutions to calcium silicates and regenerate the alkali hydroxide for further reaction with silica.

E. If the alkali hydroxides reacted with silica to form alkali silicates which could not diffuse readily through the hardened cement pastes, it should be more difficult to extract the alkalies from specimens made with reactive aggregates than from specimens made with non-reactive aggregates. Extraction data given in Table 2 show this to be the case.

For these tests 2x2x11¼-in. 1:2 mortar prisms, after storage for one week in the moist room at 70 F, were placed in distilled water in brass tubes. Each specimen was stored in water in a separate tube. Periodically, the water was replaced by fresh water and analyzed for alkalies. The data given in Table 2 were obtained for specimens made with two sands. The unreactive sand was natural Cow Bay sand from Long Island, New York (Lot 15992) and the reactive sand was rhyolitic rock (Lots 15997 and 16174) crushed and graded 0 to 4-mesh to the same grading as that of the Cow Bay sand. The rhyolitic rock and the andesitic rock (Lot 15996) referred to later were furnished by Mr. R. F. Blanks of the U. S. Bureau of Reclamation and consisted of pebbles picked from the stockpile of gravel used in the construction of Parker Dam [7] [8].

Three cements were used in making the specimens. From the known amount of cement used in each specimen and from the known alkali contents of the cements, the quantities of alkalies furnished to each specimen by the cement were calculated. These values are given in columns 4 and 5 of Table 2. The quantities of alkalies extracted during the various extraction periods are expressed as percentages of the values given in columns 4 and 5.

TABLE 2—EXTRACTION DATA FOR 2x2x11¼-IN. 1-2 MORTAR PRISMS

Cement 15914: 0.03% Na_2O; 0.19% K_2O.
" 16274: 0.28% Na_2O; 0.49% K_2O.
" 16219: 0.03% Na_2O; 0.19% K_2O.

Spec. No.	Sand	Cement Lot	Alkalies Furnished to the Prisms by the Cement-Grams		Alkalies Extracted, Cumulative at Month Indicated—% of Values in Columns 4 and 5					
			Na_2O	K_2O	Na_2O			K_2O		
					1 mo.	7 mo.	15 mo.	1 mo.	7 mo.	15 mo
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Specimens Stored at 75°F.										
453	Cow Bay	15914	.152	.967	18.5	57.4	86.4	12.5	40.7	59.1
457	Rhyolite	"	.145	.923	34.5	95.8	149.2	7.7	21.1	32.8
Specimens Stored at 110°F.										
314	Cow Bay	16219	.149	.946	62.8	216.3	322.3	22.4	62.6	80.6
312	Rhyolite	"	.139	.883	38.5	229.8	410.7	9.0	38.6	55.2
315	Cow Bay	16274	1.386	2.425	18.8	60.1	76.5	18.9	54.0	64.3
313	Rhyolite	"	1.313	2.298	9.9	34.1	53.7	7.5	23.5	32.9

Cements 15914 and 16219 contained only 0.03 percent Na_2O and both the Cow Bay sand and the rhyolitic rock sand contained appreciable quantities of Na_2O, hence a very small amount of the Na_2O liberated from the sand to the extraction water would amount to a significant percentage of the Na_2O in the cement. It probably is unsafe, therefore, to draw any conclusions from the data for the extraction of Na_2O from specimens 453, 457, 314 and 312. The extraction data for K_2O (Table 2) show that much more K_2O was extracted at any given period from the specimens made with Cow Bay sand than from the specimens made with the rhyolitic rock sand. Likewise, the data for specimens 313 and 315 made with cement 16274, which contained 0.28 percent Na_2O show a greater extraction of Na_2O from the specimen made with Cow Bay sand. These results, it seems, show that the alkalies from the cement have been converted to a less diffusible form by some component of the rhyolitic rock sand.

F. If the expansion of the concrete were produced by osmotic pressure developed by alkali silicates drawing water into the concrete, there should be a tendency for specimens in which such pressures were developing to show abnormally large gains in weight. This has been observed to be the case as is illustrated in Table 3 for specimens made with Cow Bay sand (15992) and a sand (15996) referred to above, produced by crushing an andesitic rock from Parker Dam. These prisms were stored upright in containers in which they dipped into about 1 in. of water. In general, the gain in weight, at comparable periods, for the specimens made with the andesitic rock sand are about twice those for the specimens made with the Cow Bay sand.

TABLE 3—DATA FOR CHANGES IN LENGTH AND WEIGHT OF SPECIMENS STORED AT 110 F.

Spec. No.	Cement			Sand	Gain in Weight–%		Expansion–%	
	Lot	Na_2O	K_2O		6 wk.	2 mo.	6 wk.	2 mo.
3	15942	0.64	0.46	Cow Bay	0.53	0.59	.037	.040
16	"	"	"	Andesite	0.87	1.00	.092	.176
67	14326	0.80	0.60	Cow Bay	0.34	0.41	.032	.028
75	"	"	"	Andesite	0.60	*	.174	*

*Measurements discontinued at 6-week period.

These several lines of evidence indicate that osmotic pressure plays a significant role in the reaction of aggregates with alkali hydroxides in hardened cement-pastes. Further evidence of this is given in the next section in which the behavior of $Ca(OH)_2$ towards SiO_2 is considered.

BEHAVIOR OF CALCIUM HYDROXIDE

It is well known that all forms of silica are attacked to some extent by calcium hydroxide as well as by the alkali hydroxides. Thus, an especially reactive form of silica, such as opaline silica, might be expected to react with the calcium hydroxide in the cement-paste in some manner such as indicated in equations (6) and (7).

$$SiO_2 + Ca(OH)_2 = CaSiO_3 + H_2O \quad (6)$$

$$SiO_2 + 2Ca(OH)_2 = Ca_2SiO_4 + 2H_2O \quad (7)$$

So far the evidence is that calcium hydroxide does not behave in concrete with respect to opaline silica as do the alkali hydroxides. That is, concretes made with cements containing very small amounts of alkalies, less than 0.2 percent calculated as Na_2O, and with aggregates containing opaline silica do not show expansions at all comparable with those produced when the cements are high in alkalies.

On the basis of the rates at which calcium hydroxide and alkali hydroxides in dilute solutions normally react with silica, it would be expected that in concrete the reaction between opaline silica and calcium hydroxide would be slower than that between opaline silica and alkali hydroxides. However, if the reactions with calcium hydroxide and alkali hydroxides produced comparable expansive forces per unit of reaction product, it seems that the difference between the expansions of concretes made with cements of high and low-alkali contents should not be very great. That is, both the reaction with calcium hydroxide and with alkali hydroxide should be contributing to the expansive force simultaneously with the effect of the alkali hydroxide gradually decreasing as the alkali content of the cement decreased. Since this does not appear to be the case, it seems impossible to escape the conclusion that the behaviors of calcium hydroxide and alkali hydroxides toward opaline silica in concrete differ in some manner besides the expected differences between the rates of reaction. If this conclusion is correct, any hypothesis of the mechanism whereby a reaction between opaline silica and an alkali hydroxide produces expansion in concrete must explain why calcium hydroxide does not similarly produce excessive expansions.

Since calcium silicates are only very slightly soluble, they are not capable of producing osmotic pressures to any significant extent. Hence, the formation of a small amount of calcium silicate on the surface of a particle of SiO_2 would not tend to draw more solution to the particle and cause the reaction to proceed as is the case with the formation of a small amount of alkali silicate. In fact, the formation of a film of calcium silicate on the surface of the particle of SiO_2 might conceivably act to seal the particle against further attack by $Ca(OH)_2$. This might also

be an effective seal against the small amounts of alkali hydroxides available from cements of low-alkali content.

Undoubtedly, if the hardened cement-paste is impermeable to the alkali silicates, it must also be impermeable to the calcium silicates. Hence, it does not appear possible to explain the difference between the behavior of $Ca(OH)_2$ and alkali hydroxides either on the basis of the lack of reactivity between opaline silica and $Ca(OH)_2$ or on the basis of a difference in the permeability of the cement-paste toward the reaction products. It seems, therefore, that the difference between these hydroxides must be explained on the basis of the solubilities of the reaction products. That is, the insoluble calcium silicate tends to protect the SiO_2 from attack, whereas the soluble alkali-silicates tend to accelerate the attack. Hence, the observed behavior of calcium hydroxide is in agreement with the osmotic pressure hypothesis.

OTHER REACTIVE AGGREGATES

This discussion has been limited to the reaction of opaline silica and alkali hydroxides because at present a reaction between opaline silica and alkali hydroxides in concrete appears to be established definitely, whereas such is not the case with other components of aggregates. However, if other materials such as the glass which occurs in certain of the eruptive rocks were readily attacked by the alkali hydroxides and produced alkali silicates, their behavior in concrete should be identical with that of opaline silica.

It should be pointed out that according to this hypothesis, abnormal expansions would not be expected unless the reaction between the aggregate and the alkali hydroxides produced a material incapable of diffusing through the cement-paste. Certain forms of alumina might behave like opaline silica because the alkali aluminates are relatively soluble and might also form ions which could not diffuse through the cement pastes.

It is conceivable that feldspars and similar alkali-bearing minerals might tend to exchange alkali oxides for calcium oxide in the concrete, as illustrated in equation (8).

$$Na_2O.Al_2O_3.6SiO_2 + Ca(OH)_2 = CaO.Al_2O_3.6SiO_2 + 2NaOH \quad \ldots (8)$$

This reaction would not be expected to cause any appreciable expansion because the calcium alumino-silicate formed would be insoluble and hence incapable of producing an osmotic pressure, and the soluble $NaOH$ could diffuse through the cement-paste. However, if the aggregate contained opaline silica in addition to these alkali-bearing minerals, the $NaOH$ liberated by a reaction, such as illustrated in Equation (8),

TABLE 4—EXTRACTION DATA FOR MORTAR PRISMS MADE WITH DIFFERENT SANDS

Spec. No.	453	454	455	456	457	453	454	455	456	457
Sand Lot	15992	15994	15886	15996	15997	15992	15994	15886	15996	15997
Alkalies in	Na_2O					K_2O				
Cement*-grams	.152	.150	.151	.143	.145	.967	.950	.961	.908	.923
Alkalies Extracted, %**										
1 mo.	18.5	20.8	25.9	78.8	34.5	12.5	14.5	19.0	14.0	7.7
3 mo.	34.2	41.4	51.3	153.8	60.6	25.6	29.8	36.7	29.2	13.6
5 mo.	46.6	56.8	68.6	205.8	78.4	34.1	40.0	48.5	40.6	17.0
7 mo.	57.4	72.3	85.5	251.8	95.8	40.7	47.9	56.7	50.4	21.1
9 mo.	66.9	88.8	101.3	293.1	111.7	46.1	54.9	63.5	58.8	24.2
11 mo.	73.5	101.0	115.0	327.2	126.3	50.9	59.9	68.1	66.3	27.2
15 mo.	86.4	127.6	142.3	387.2	149.2	59.1	68.7	76.0	80.0	32.8

*Grams of alkalies furnished to the specimens by the cement.
**Alkalies extracted expressed as percent of values given in the first line.

TABLE 4A—PARTIAL OXIDE COMPOSITION OF SANDS—PERCENT BY WEIGHT

Lot	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O
15886	58.88	20.19	7.24	1.21	1.96	1.60	3.71
15992	87.48	5.84	2.34	1.15	0.53	0.62	0.92
15994	64.75	16.59	5.01	4.41	2.11	3.09	3.10
15996	66.41	16.45	2.76	1.71	0.99	2.87	6.27
15997	71.40	14.30	1.89	2.38	0.57	3.41	4.13

could react with the opaline silica to produce expansions in the concrete. It is theoretically possible, therefore, for the reactions of Equations (1) and (2) to obtain the required alkali hydroxide from some component of the aggregate instead of from the cement.

Studies are under way in this laboratory to determine the extent to which alkali-bearing minerals might liberate alkalies in concrete. In this study the rocks under investigation are crushed and graded, 0 to 4-mesh, to the grading used in the laboratory for Cow Bay sand. These sands are made into 2x2x11¼-in. 1-2 mortar prisms and after storage for 7 days in the moist room, each prism is stored in a separate brass container in about 700 ml. of distilled water. After 1 mo. and at 2-mo. intervals thereafter the water is replaced by distilled water and analyzed for Na_2O and K_2O.

The data obtained from these studies with five sands and one cement of low alkali content (0.03 percent Na_2O; 0.19 percent K_2O) are given in Table 4. From the known cement content of each prism and the

known alkali content of the cement, the quantities of alkalies in each specimen were calculated and are given in the first line of Table 4. The alkalies extracted at the periods indicated are expressed as percentages of the values in this first line.

The chemical compositions of the aggregates are given in Table 4A. Cow Bay sand (15992) from Long Island, New York, was used as a control sand because it was believed that the small amount of feldspar and mica minerals in this sand would not liberate appreciable quantities of alkalies in mortars. Lot 15994 is a granite from Florence Lake, Calif., and Lot 15886 is the phyllite used as coarse aggregate in the Buck Falls hydro-electric plant in Virginia [5]. Both the granite and phyllite were obtained from Prof. R. W. Carlson. Lots 15996 and 15997 were obtained from Mr. R. F. Blanks as representative, respectively, of the andesitic and rhyolitic pebbles* in the gravel used in Parker Dam.

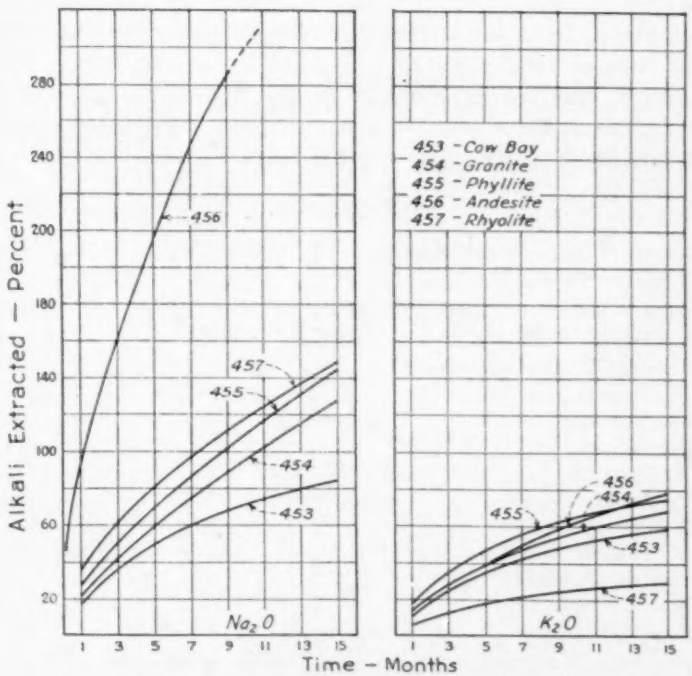

Fig. 1—Rate of extraction of alkalies from mortar prisms—75 F.

The data obtained in this study are plotted in Fig. 1. It is seen from these plots that at 15 months the quantity of Na_2O extracted from the

*It should be noted that the sands produced from these pebbles may have contained minerals which are not common to all andesitic and rhyolitic rocks; hence, the results presented for these materials are not necessarily indicative of the results to be expected from other andesitic and rhyolitic rocks.

specimen made with the andesitic sand (15996) is approximately four times the quantity contributed to the specimen by the cement. In the case of the specimens made with the other sands, except Cow Bay, the Na_2O extracted at 15 months is slightly greater than that contributed by the cements, and from the slopes of the curves, it appears that these specimens will continue to liberate Na_2O for some time. Hence, it appears that a part of the Na_2O in all of these sands, except possibly Cow Bay sand, slowly becomes water-soluble and diffuses through the hardened cement-paste.

In none of the specimens has the K_2O extracted at 15 mo. equalled the quantity carried by the cement, and, except for the andesitic sand (15996) the slopes of the curves show that the rate of extraction is decreasing. Hence, it appears that the tendency for the K_2O in these sands to become water soluble is much less than it is for Na_2O.

In the case of K_2O, it is interesting to observe the slow rate at which K_2O is extracted from the specimen made with rhyolitic sand (15997). This slow rate of extraction, as was pointed out previously, probably is an indication that some component of the rhyolitic sand has combined with the K_2O from the cement in a manner which decreased the rate at which it could diffuse through the hardened cement-paste.

BIBLIOGRAPHY

(1) Influence of Cement and Aggregate on Concrete Expansion, by Thomas E. Stanton; *Eng. News-Record 124*, 59 (Feb. 1, 1940).

(2) Expansion of Concrete through Reaction between Cement and Aggregate, by Thomas E. Stanton; *Proc. Am. Soc. C. E. 66*, 1781 (1940).

(3) Discussions of the above paper:

R. W. Carlson	*Proc. Am. Soc. C.E. 67*, 265 (1941)
Bailey Tremper	" " " " *67*, 509 (1941)
Hubert Woods	" " " " *67*, 671 (1941)
N. T. Stadtfeld	" " " " *67*, 672 (1941)
W. C. Hanna	" " " " *67*, 899 (1941)
J. C. Witt	" " " " *67*, 903 (1941)
R. F. Blanks	" " " " *67*, 904 (1941)
J. MacNeil Turnbull	" " " " *67*, 1104 (1941)
Robert A. Kinzie	" " " " *67*, 1106 (1941)
Thomas E. Stanton	" " " " *67*, 1402 (1941)

(4) Much Ado over Alkalies and Sulfates in Portland Cement, by Alton J. Blank, *Concrete* (CMS) *49*, 182, 188 (1941).

(5) Investigation of Causes of Delayed Expansion of Concrete in Buck Hydroelectric Plant, by H. A. Kammer and R. W. Carlson; ACI JOURNAL, June, 1941; *Proceedings* V. 37, p. 665.

(6) Evidence in Washington of Deterioration of Concrete through Reaction between Aggregate and High Alkali Cement, by Bailey Tremper; ACI JOURNAL, June 1941; *Proceedings* V. 37, P. 673.

(7) Concrete Deterioration at Parker Dam, by R. F. Blanks; *Eng. News-Record 126*, 46 (Mar. 27, 1941)

(8) Cracking in Concrete Due to Expansive Reaction between Aggregate and High Alkali Cement as Evidenced in Parker Dam, by H. S. Meissner; ACI JOURNAL, Apr. 1941; *Proceedings* V. 37, p. 549.

(9) California Experience with the Expansion of Concrete through Reaction between Cement and Aggregate, by Thomas E. Stanton, O. J. Porter, S. Meder, and Allen Nicol; ACI JOURNAL, Jan. 1942; *Proceedings* V. 38, p. 209.

(10) Expansion of Concrete due to Reaction between Andesitic Aggregates and Cement, by Howard A. Coombs; *Am. J. of Sci. 240*, 288 (1942).

(11) The Nature of the Process Leading to the Disintegration of Concrete with Special Reference to Excess Alkalies, by Charles P. Berkey; ACI JOURNAL, June 1941; *Proceedings* V. 37, p. 689.

(12) Discussions of Paper by Stanton, Porter, Meder, and Nicol (9), by H. S. Meissner, Roger Rhoades, Lewis H. Tuthill, Roy W. Carlson, C. H. Scholer, R. E. Davis, J. C. Witt, and T. E. Stanton; J. Am. Concrete Inst. Supplement to ACI JOURNAL, Nov. 1942; *Proceedings* V. 38, p. 236-1 to 236-39.

(13) Detecting Free Lime and Magnesia in Portland Cement, by L. S. Brown and M. A. Swayze; *Rock Products 41* (6) 65 (1938).

Discussion of this paper should reach the ACI Secretary in triplicate by April 1, 1944 for publication in the JOURNAL for June 1944.

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Discussion of a Paper by W. C. Hansen:

Studies Relating to the Mechanism by Which the Alkali-Aggregate Reaction Produces Expansion in Concrete*

By BAILEY TREMPER, THOMAS E. STANTON, GEORGE L. KALOUSEK and AUTHOR

By BAILEY TREMPER†

The curves presented in Fig. 1 and the data in Table 4 of Mr. Hansen's paper offer good evidence that Na_2O is being liberated from its chemical combination in the original minerals of the aggregates. This is particularly true of the andesite. The author's method of expressing the amount of extracted Na_2O (as a percentage of the Na_2O content of the cement) makes for a striking demonstration but tends to overemphasize the significance of the reaction in terms of concrete durability.

The cement used in this test contains the unusually low amount of 0.03 per cent Na_2O. Although the extracted Na_2O up to 15 months was nearly four times that contributed by the cement, the amount was only 0.12 per cent of the cement. The conditions of test seem to be such that the major portion of the Na_2O is found in the extract water. Since the original cement contained 0.03 per cent Na_2O and the amount extracted was 0.12 per cent the increase was 0.09 per cent. Such an increase ordinarily is of minor consequence in influencing the degree of alkali-aggregate reactions.

The slope of the curve for the andesite specimen No. 456 in Fig. 1 is very steep. Unless the data are studied carefully, one may be led to the conclusion that it will be only a matter of a few years until the Na_2O liberated from the aggregate is sufficient in amount to offset completely any advantage in using a low-alkali cement as a preventative of delayed expansion. Having reached such a conclusion it is but a step further to the decision that reactive aggregates are, of themselves, "bad" and can-

*ACI JOURNAL Jan. 1944; *Proceedings* V. 40, p. 213.
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not be used safely with any cement. Finally, one might conclude that since concrete made with reactive aggregates is doomed to eventual failure, the logical method of attack is to eliminate all such aggregates and cease worrying over the alkali content of the cement.

In the following paragraphs the writer will attempt to show that such a line of reasoning based on the data presented is entirely fallacious.

The data of Table 4 for specimen 456 may be expressed quite accurately by the equation:

$$a = 2.6\, t^{0.55} \qquad (1)$$

in which a is the extracted Na_2O expressed as hundredths of one per cent of the cement and t is the time in months.

Below are shown the author's values for extracted Na_2O, the same values in terms of percentage of the cement and the values computed from the above equation:

Time in months	Na_2O Extracted		as computed from equation (1)
	as per cent of Na_2O in cement	as per cent of cement	
1	78.8	0.023	0.026
3	153.8	0.046	0.047
5	205.8	0.062	0.063
7	251.8	0.076	0.076
9	293.1	0.088	0.087
11	327.2	0.098	0.098
15	387.2	0.116	0.116
24			0.150
48			0.219
96			0.317

It will be noted that if there is no change in trend the extracted Na_2O will have amounted to only 0.22 per cent after 4 years and 0.32 per cent after 8 years.

The specimen under test contains gravel aggregate crushed to 0 to No. 4 size. The mix is rich, 1:2. It is kept continuously saturated and at a temperature which is high in terms of yearly average outside conditions. It is difficult to estimate to what extent the conditions of test accelerate similar reactions in normal concrete exposed out of doors. It seems safe to conclude, however, that the rate is at least two- or three-fold.

With the values given above for rate of liberation of Na_2O from the aggregate in mind, there should be little cause for concern as to harmful expansion in normal concrete when the cement itself is low in alkalies.

By THOMAS E. STANTON*

Hansen's contribution is a fine presentation from an analytical standpoint of the most probable source of the expansive pressures. The evidence submitted by him in support of the osmotic pressure hypothesis is impressive.

It will be recalled that in the original California studies† while it was concluded "although it appears very probable that some form of hydrous silica plays a very active part, the greatest reaction in the tests described herein has been with material classified as a siliceous magnesian limestone (No. 28039)."

In our search for the reactive ingredient or ingredients in the aggregate we had conducted a series of tests on the different types of shale and chert found in the known reactive commercial aggregate (Oro Fino).

Specimens were made adding 10 per cent of five of these segregated shales or cherts, including the siliceous magnesian limestone No. 28039 and the opaline chert No. 28038, to a neutral sand (Table 1 of the Am. Soc. of C.E. paper). At the end of one year the only serious expansion which had developed in this 1:3 mortar series was in the case of the siliceous magnesian limestone, identified as No. 28039, the expansion in this case being over 0.6 per cent. It was not until later that it was found that an overdose of the high opal content chert No. 28038 had resulted in no appreciable expansion with this rock, and it was then discovered that there is an optimum percentage for any active rock (subsequently determined in the California case to be with relation to the opal content) and that the expansive effects of No. 28038 increases up to about 5 per cent of this reactive chert, which contains 80 to 85 per cent opal, and then falls off to a negligible amount with 10 per cent or more; whereas the expansive effects of the siliceous magnesian limestone No. 28039, which normally contains less than 20 per cent opal, increases to a peak at approximately 20 per cent and then falls off to a neglibible amount with 50 to 60 per cent.

These phenomena not having developed at the time of the first analyses combined with the fact that the only apparent highly reactive aggregate was the one which had a high content (27 to 30 per cent) of magnesian carbonate it was decided that:

> "*If* it is due in any part to the magnesian carbonate, the probable chemical reactions in this respect are as follows: The sodium oxide in the cement hydrates to form sodium hydroxide; the sodium hydroxide in turn probably reacts with at least some form of the

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†Proceedings, American Society of Civil Engineers, Dec. 1940.

magnesian carbonate in the siliceous magnesian limestone to form magnesian hydroxide and sodium carbonate; thus $MgCO_3 + 2\ NaOH \longrightarrow Mg(OH)_2 + Na_2CO_3$."

It was then pointed out that the combined volume of the assumed reaction products was 239 per cent greater than the combined volume of the reacting components, thereby affording a plausible explanation for the expansive action.

At the same time it was pointed out that a sodium silicate gel was found throughout broken sections of concrete as well as exuding on the surface through pores and cracks.

In the meantime, other specimens had been made adding from 2.5 to 10 per cent of various shales and cherts to a neutral sand and another series containing from one quarter of one to 15 per cent of the highly reactive opaline chert No. 28038 (Tables 12 and 13 American Society of Civil Engineers Transactions Vol. 107 1942).

From these later tests it was determined that the reason no expansion had previously been noted with No. 28038 was that an excess had been used and that apparently the greatest expansion might be anticipated with approximately 3 per cent.

It may be of interest at this point to present some long time (24 months) results of this original test with No. 28038 and a high alkali cement (1.14 per cent Na_2O).

Per cent No. 28038 Added to a Neutral Sand	Per cent Expansion 24 Months
0.25	0.112
0.50	0.656
0.75	0.746
1.00	0.822
2.00	1.351
3.00	1.543
4.00	1.801
5.00	1.824
10.00	0.025

Therefore, while it was definitely determined that the source of the gel and the cause of the trouble in California was the opaline silica in the chert which on reaction with sodium hydroxide in the cement formed the silica gel; nevertheless, as this gel in the initial stages contains a high moisture content and is plastic, it was difficult to conceive how it could be productive of the extremely high pressures requisite for the disruptive action particularly as in a dry state the space required for the reaction products would be less than that required by the alkali hydroxides. Hansen has offered the first plausible solution of the problem.

He makes other significant observations under the heading "Other Reactive Aggregates" (Page 223).

1. ". . . . if other materials such as the glass which occurs in certain of the eruptive rocks were readily attacked by the alkali hydroxides and produced alkali silicates, their behavior in concrete should be identical with that of opaline silica."

In support of this thesis attention is herein directed to the description of studies under way in California under the heading "Studies of Minerals other than Opal."*

These studies included a synthetic andesite glass having a chemical composition equivalent to that of an average andesite. This glass was manufactured in the laboratory of the California Division of Highways by fusing the several ingredients into one mass of glass, with an oxyacetylene torch. The composition of this glass is given in Table E of the report* and the expansive reactions when the glass is added in varying percentages to a mortar of neutral sand and high alkali cement are shown in Table F thereof.

Attention was called to the relatively high expansion in six months when the specimens were cured in sealed containers at 130 F. There was little noticeable expansion, however at 70 F. nor has the subsequent expansion up to 18 months been appreciable at the lower temperature, although the expansion at 130 F. has continued to a peak of 0.455 per cent in the case of the 30 per cent addition.

The following observations were made (p. 236-30):

Observations of many andesite specimens known to be reactive indicated that they were moderately or partially altered and weathered. This condition was existent prior to fabrication into concrete. Work done by Evans and Willinms in Lassen Volcanic National Park shows a few rocks in the vicinity of hot springs to be highly altered with opal as a principal constituent.

To simulate the Lassen Park condition, some of the synthetic andesite glass has been altered in the presence of SO_2 and water for comparison of expansive reaction with fresh glass. Various methods of alteration were tried without much success until, after consulting the literature, sulphur dioxide was tried.

A portion of the untreated synthetic andesite glass, crushed to —20 +50 mesh size, was placed in a long glass tube, moistened with water and subjected to daily evolution of SO_2 from a cylinder. A petrographic study of the SO_2—H_2O treated glass up to the present time indicates that there has been a definite change not only in the appearance of the material but also in its composition and refractive index. The treatment will be continued for a few months longer before fabrication of the altered glass into expansion bars.

Subsequent to writing the above, tests on specimens of this weathered synthetic andesite were started in December, 1942, and therefore test data are now available over a 12-month period.

These test data at various ages in comparison with the unweathered glass are shown in Table A of this discussion. A definite excessive reaction at 70 F. is now apparent reaching a peak with 20 per cent of the glass and falling off to a negligible amount with 30 per cent. At the

*ACI JOURNAL Supplement, Nov. 1942 *Proceedings* V. 38, p. 236-28.

TABLE A

Per cent expansion of 1:2 mortar specimens of a high alkali cement (1.07 per cent) and fine aggregate consisting of Russian river sand and different percentages of synthetic andesite glass (weathered and unweathered) substituted for an equivalent percentage of the neutral Russian river sand.

Per cent Synthetic Andesite Glass	Age at Test	Per cent Expansion			
		Unweathered		Weathered	
		0 F.	130 F.	70 F.	130 F.
5	28 Days	.004	.009	.005	.011
	3 Mos.	.011	.021	.012	.026
	6 Mos.	.013	.022	.018	.029
	12 Mos.	.015	.044	.024	.054
10	28 Days	.007	.021	.010	.020
	3 Mos.	.013	.071	.143	.046
	6 Mos.	.008	.116	.213	.119
	12 Mos.	.012	.167	.218	.272
20	28 Days	.003	.032	.007	.029
	3 Mos.	.016	.163	.063	.123
	6 Mos.	.018	.233	.363	.345
	12 Mos.	.022	.308	.461	.486
30	28 Days	.008	.115	.000	.014
	3 Mos.	.013	.307	.008	.055
	6 Mos.	.017	.398	.015	.149
	12 Mos.	.025	.455	.022	.418

Composition of Synthetic Andesite Glass

SiO_2	61.8%
Al_2O_3	18.8%
Fe_2O_3	2.5%
CaO	7.6%
MgO	4.0%
Na_2O	3.0%
K_2O	1.2%
Undetermined	1.1%
Total	100.0%

same time the reaction of the weathered as compared with the unweathered glass does not appear to have been materially altered at 130 F.

It therefore appears conclusive that weathered andesite of the type included in this test series is definitely more reactive at normal temperatures (70 F.) than the unweathered product.

Hansen concludes that:

Certain forms of alumina might behave like opaline silica because the alkali aluminates are relatively soluble and might also form ions which could not diffuse through the cement pastes.

The California synthetic andesite contained approximately 18.8 per cent Al_2O_3.

Hansen then observes:

It is conceivable that felspars and similar alkali-bearing minerals might tend to exchange alkali oxides for calcium oxide in the concrete.

and that:

While this reaction would not be expected to cause any appreciable expansion because the calcium alumnio-silicate formed would be insoluble and hence incapable of producing an osmotic pressure and the soluble *NaOH* could diffuse through the cement-paste—however, if the aggregate contained opaline silica in addition to these alkali-bearing minerals, the *NaOH* liberated by the reaction—could react with the opaline silica to produce expansion in the concrete . . . . It is theoretically possible there fore . . . . to attain the required alkali hydroxide from some component of the aggregate instead of from the cement.

This hypothesis may account for the fact that some investigators have observed the development in a comparatively short time of an excessive expansion with a relatively low alkali cement in combination with a presumably unreactive aggregate to which had been added the reactive opaline chert.

That this might be the case was recognized some time ago by this department and tests have been under way for several months to compare the relative reactivity of low alkali cements in combination with fine aggregates, analyzing relatively high in Na_2O to which have been added 10 per cent of the siliceous magnesian limestone No. 28039 in comparison with other fine aggregates containing a percentage negligible of Na_2O.

These tests have not been under way long enough to develop conclusive data although the results to date tend to definitely confirm Hansen's suggestion.

By GEORGE L. KALOUSEK*

The author has presented an interesting hypothesis that goes a long way towards explaining the mechanism by which the alkali-aggregate reaction causes expansion of concrete. Some aspects of the mechanism, such as the manner in which the membrane is formed and how the process gets started, however, merit further consideration.

A series of investigations at the National Bureau of Standards was concerned, in part, directly with the alkali-aggregate reaction. Although, some of these studies are not yet completed it seems appropriate, notwithstanding, to give a resume of the more pertinent results and the interpretations based on them regarding the processes causing expansion. The results of the study of the system soda-lime-silica-water at 25 C† may be applicable towards a more complete explanation of the nature and formation of the semipermeable membrane.

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†Publication pending

The author has demonstrated that a thimble of cement paste, when filled with sodium silicate, functioned as a semi-permeable membrane, an osmotic pressure of several inches of water being developed. It was also pointed out that the cement paste is not necessarily completely impermeable to the alkali silicates. Since the pressure causing expansion of concrete must be of a rather large magnitude it is possible that the membrane formed around an opal particle in concrete may be of a different nature than that of cement paste alone. The product of the reaction involving the constituents soda, lime, silica and water† is a soda-lime-silicate gel. The formation of this gel in concrete at the opal-alkali solution interface would probably make the cement paste impermeable to the silicate solution. The process may be as follows:

The sodium hydroxide appearing in solution reacts with the opal and forms an aqueous solution of sodium silicate in the proximity of the opal particles. At the start of the process, the sodium silicate diffusing a short distance into the surrounding paste would, upon coming into contact with the $Ca(OH)_2$, be precipitated in part as a soda-lime-silicate gel. The amounts of the gel would increase as the reaction proceeds and the deposit might extend some distance into the surrounding cement paste. Eventually, it would seem, the available openings in the cement paste would fill with the gel. The composite of the cement paste and the gel might then be regarded as the membrane.

The question may arise if the alumina- and iron-bearing materials in cements are necessary for the formation of the membrane or if they cause expansion directly by forming voluminous crystalline hydrates. In order to obtain information on this point it seemed desirable to measure the expansion of specimens the cementitious material of which consisted of tricalcium and dicalcium silicates in different proportions with gypsum, and with and without additions of various amounts of tricalcium aluminate and tetracalcium alumino ferrite. The specimens made of a 1:2 mortar contained 2.5 per cent of opal by weight of sand and 1.0 per cent of Na_2O or K_2O (computed as Na_2O) by weight of cement. Although the study is not yet completed the available data indicate that the expansions of the specimens are independent of the compositions of the cementitious material and the kind of alkali used. Since the additions of the alumina- or iron-bearing materials caused no definite change in expansion it is reasonable to assume that these constituents are neither necessary to the formation of the membrane nor do they result in expansion by forming crystalline hydrates.

Another suggested cause of expansion that appeared to merit consideration was the possible formation of crystalline alkali-silicate hydrates, or alkali-lime-silicate hydrates. Accordingly, in the study of the system

soda-lime-silica-water at 25 C, the reaction products obtained at 4 to 18 weeks were carefully examined for crystalline phases, but none was found. Crystallization of such compounds at ages greater than 18 weeks could not account for the expansions observed in the specimens described in the preceding paragraph because significant expansions were obtained after 1 or 2 weeks.

The foregoing results indicate that the expansions are not caused by the precipitation of voluminous crystalline hydrates and, therefore, indirectly support the theory advanced by Hansen.

AUTHOR'S CLOSURE

Mr. Tremper's calculations for specimen 456 are interesting and instructive, and his discussion is very significant. The author agrees with Mr. Tremper that the data presented should not lead to the conclusion that all aggregates showing reactivity in laboratory tests should be eliminated from use in concrete. The object in presenting these data on the release of alkalies by aggregates was to call attention to the need of considering the aggregate as a whole as well as specific components which might react with alkalies. While no cases have been reported in which the disintegration of concrete was traced wholly or in part to a reaction between components of the aggregate, these data suggest that this is a possibility which should not be overlooked. It is interesting to note that Mr. Stanton also has considered this possibility.

The discussion and data presented by Mr. Stanton add materially to the information on this subject of reactive aggregates. It is gratifying to know that he finds the ideas and data presented in the paper helpful in explaining some of his observations.

The suggestion by Dr. Kalousek that the alkali silicates, formed by the reaction of opaline silica with alkali hydroxides, contribute to the formation of the membrane seems entirely plausible and merits consideration in further studies of this problem. His observations that the expansions are independent of the compositions of the cementitious material and that crystalline alkali or alkali lime silicate hydrates are not formed in his products up to ages of 18 weeks are important contributions to this subject.

Our attention has been called to the fact that the ordinates of Fig. 1 are misnumbered. Starting at 200 the values shown should be increased by 20. The data from which the figure was plotted are given in Table 4.

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Alkali Etching Tests on Concrete Aggregates*

By WILLARD H. PARSONS and HERBERT INSLEY†

SYNOPSIS

A test for determining the reactivity of an aggregate with high-alkali cements is described, which consists of microscopic examination of polished surfaces of rocks and minerals after etching in various alkaline hydroxide and sulphate solutions. Pure opal, opaline chert and opaline limestone are readily etched, while volcanic glass, certain feldspars, chalcedony, calcite, and dolomite are slightly etched under some of these test conditions. Photomicrographs of etched rocks and minerals are included.

I. INTRODUCTION

A type of disintegration of concrete accompanied by considerable expansion has been ascribed by Stanton, Porter, Meder and Nicol‡, and by others**to a reaction between certain types of aggregate and the alkalies†† originally present in the cement. Although it has been generally agreed that such reactions are possible and that there is an apparent causal relation between the reaction and the expansion that follows or accompanies it, there has been no general agreement on:

1. The type of minerals or rock constituents in the aggregate, with the exception of opaline silica, which may react with the alkalies in the cement.

2. The mechanics of the reaction whereby it may cause expansion.

3. The limiting quantity of alkali in the cement below which no expansion takes place.

4. A rapid and reliable test method to identify reactive constituents in aggregate material.

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†National Bureau of Standards, Washington, D. C.
‡Thomas E. Stanton, O. J. Porter, L. C. Meder, and Allen Nicol, California experience with the expansion of concrete through reaction with cement and aggregate, ACI JOURNAL, Jan. 1942; *Proceedings*, V. 38, p. 209-236.
**See references in paper by T. E. Stanton, et al.
††The term "alkalies" as used in the present paper refers to the oxides of sodium and potassium.

As a part of a general study at the National Bureau of Standards of the properties of concrete aggregate materials, an etching test has been developed for determining what minerals may react with the solutions found in set or setting cements, and which appears to offer a short, simple test for determining the reactivity of an aggregate. The present paper contains a description of the test and the results thus far obtained.

II. DESCRIPTION OF METHOD AND MATERIALS

In this investigation, microscopical examination was made of the polished surface on minerals and rocks to determine whether the surface was attacked after immersion of the specimen in various etchants.

1. Etchants

The etchants used were of three types:

(a) Solutions of single compounds.

(b) Mixed solutions based on extracts from clinkers.

(c) Neat portland cement pastes.

(a) *Solutions of single compounds.* Solutions containing single compounds in the following concentrations were used: 10 percent $NaOH$, 10 percent KOH, saturated $Ca(OH)_2$, and 10 percent K_2SO_4. The solutions of $NaOH$ and KOH, with immersed specimens, were maintained at various temperatures within the range of 20 to 90 C and for periods within the range of 1 to 17 hours. Extended periods, to a total of 9 months, were employed with solutions of $Ca(OH)_2$ and K_2SO_4. In the long-time tests care was taken to avoid contamination by CO_2.

(b) *Mixed solutions based on extracts from clinkers.* Three etching solutions based on clinker extracts* were made up as follows:

	Additions in grams per liter		
	Solution No. 1	Solution No. 2	Solution No. 3
$Ca(OH)_2$	1.9	1.4	—
$CaSO_4$	1.7	—	3.2
KOH	.3	6.6	.4
K_2SO_4	—	25.5	—
$NaOH$	.1	.7	3.5
Na_2SO_4	—	—	1.2

NOTE: Complete solution of all these additions did not take place, since the values given above were based on analyses of supersaturated solutions.

Polished specimens were placed in these solutions at room temperatures and at 40 C for periods up to nine months. Care was taken to keep out CO_2.

(c) *Neat portland cement pastes.* Polished specimens were embedded in pastes made with either a cement of high Na_2O content (1.1 per cent

*George L. Kalousek, C. H. Jumper and J. J. Tregoning, Composition and physical properties of aqueous extracts from portland cement clinker pastes containing added materials, *J. Research* NBS, 30, 215-255 (1943).

Na_2O) or with a cement of high K_2O content (1.2 percent K_2O) and kept moist at room temperatures for 60 days. The specimens were then broken out of the hardened pastes and examined for evidences of etching.

2. Materials

In selecting aggregate materials for etching studies, rocks were primarily chosen which had been suggested as being susceptible to attack by alkalies. Other materials were chosen whose behavior was doubtful or unknown. In order to reduce the number of factors affecting the results, tests were made also on a number of the pure minerals which compose these rocks. These minerals included opal, whose lack of resistance to alkaline attack is notorious*, other crystalline and amorphous forms of silica, various types of feldspar, calcite, and dolomite. The siliceous glasses occurring in some extrusive igneous rocks have been suggested as being responsible for expansive disintegration of concrete† and, therefore, types of such rocks containing large amounts of these glasses were selected because it was not practical to concentrate the glasses in the pure forms from the rocks or to synthesize the glasses themselves.

The name, source, and description of the rocks and minerals used are given in Table 1.

III. RESULTS

Opal

A green, waxy-looking opal from Nevada was placed in all of the etchants. In $NaOH$ and KOH the surface was distinctly etched in 20 minutes and the polish completely removed in 1 hour at 50 C (Fig. 1 and 2). In a week at room temperature the surface became thickly coated with gel formed at the expense of the opal. In K_2SO_4 a very slight etch was apparent in 2 hours at 60 C, but after two months at room temperature, the surface still was not etched completely. In a total of 8 months the surface was roughened and clouded, but no gel had formed. Saturated $Ca(OH)_2$ did not etch the opal after 8 months immersion at room temperature. At 40 C, however, for the same time, the surface was strongly etched but without gel formation. A California opaline shale specimen (No. 21, Table 1), sent in by Mr. Hanna‡, partially disintegrated and swelled in saturated $Ca(OH)_2$ solution in one week.

In the clinker extract solutions the following results were obtained at room temperatures (20 - 25 C): the potassium-rich solution (No. 2)

*T. E. Stanton, et al., op. cit.
†Howard A. Coombs, Expansion of concrete due to reaction between andesitic aggregate and cement, *Am. J. Sci.* 240, 288-297 (1942).
‡W. C. Hanna, J. C. Witt, and R. F. Blanks, Expansion of concrete through reaction between cement and aggregate, Discussion, *Proc.* Am. Soc. C. E., 67, 900-901 (1941).

TABLE 1—SOURCE AND DESCRIPTION OF ROCKS AND MINERALS ETCHED

No.	Name	Source	Description and remarks
1	Opal	Virgin Valley, Nevada	Waxy, massive; relic diatom structures.
2	Opaline chert	San Luis Obispo, Calif.	Brown, banded opal with about 10 percent of chalcedony.
3	Si-Mg limestone	Paso Robles, Calif.	Contains 5-10 percent of opal and 5-10 percent of chalcedony interstitial to dolomite and replacing fossils and glass shards.
4	Chalcedony	Serra do Mar, Brazil	Microfibrous structure, banded.
5	Quartz	Mitchell Co., N. C.	Single crystal in feldspar.
6	Chert	Potomac River gravel, Maryland - Virginia	Black and white cherts; microcrystalline quartz, traces calcite, limonite.
7	Microcline feldspar	Bathurst, Ont.	A perthite with 10 percent of albite, trace of quartz. Single crystal fragment.
8	Oligoclase feldspar	Mitchell Co., N. C.	Single crystal fragment; traces of muscovite and quartz.
9	Bytownite feldspar	Unknown	Mosaic of small crystals; traces of chlorite, calcite and various zeolites. The latter are etched in some solutions.
10	Hornblende	Renfrew Co., Ont.	Single crystal fragment; many inclusions of feldspar, mica and pyrite.
11	Obsidian	Lake Co., Oregon	99 percent volcanic glass, 1 percent feldspar,
12	Pitchstone	Magdalena Mountains, New Mexico	65-75 percent volcanic glass, rest feldspar and quartz; only glass etched.
13	Rhyolite	White Pine Co., Nevada	50 percent glass; rest orthoclase feldspar. quartz and biotite; only glass etched.
14	Andesite	Bill Williams Aggregate (Parker Dam), Arizona	20-30 percent volcanic glass; rest andesine feldspar, biotite, magnetite; only glass etched.
15	Phyllite	Buck Dam, Virginia	Fine-grained microcrystalline quartz and chalcedony, mica, calcite and traces of feldspar, chlorite, limonite.
16	Serpentine	Hoboken, N. J.	Massive, variety antigorite.
17	Calcite	Taos Co., New Mexico	Pure, single crystal fragment.
18	Dolomite	Tuckahoe, New York	Coarse-grained dolomite marble.
19	Dolomitic limestone	Norwood, New York	Fine-grained dolomite; 3-5 percent quartz.
20	Si-Mg limestone	Paso Robles, Calif.	Fine-grained dolomitic limestone with 15-20 percent of silica (see No. 3 for description of silica minerals).
21	Opaline shale	Piru, Calif. (?)	Fine-grained shale composed of intimate mixture of opal, clay minerals and carbonates with veinlets of chalcedony.

completely etched the opal and formed some gel in 10 days, the sodium-rich solution (No. 3) gave a slight etch in 50 days and a complete etch and abundant gel in 8 months, while the low alkali solution (No. 1) did not etch the opal at all, even in 8 months. At 40 C, however, the solution of low alkali concentration etched the opal slightly in 3 months, and after 9 months strongly but without gel formation.

Opal specimens in neat cement pastes of sodium-rich and potassium-rich types had a distinct reaction rim (Fig. 3) after 2 months. The rim consisted of a gel which dried to a white powder.

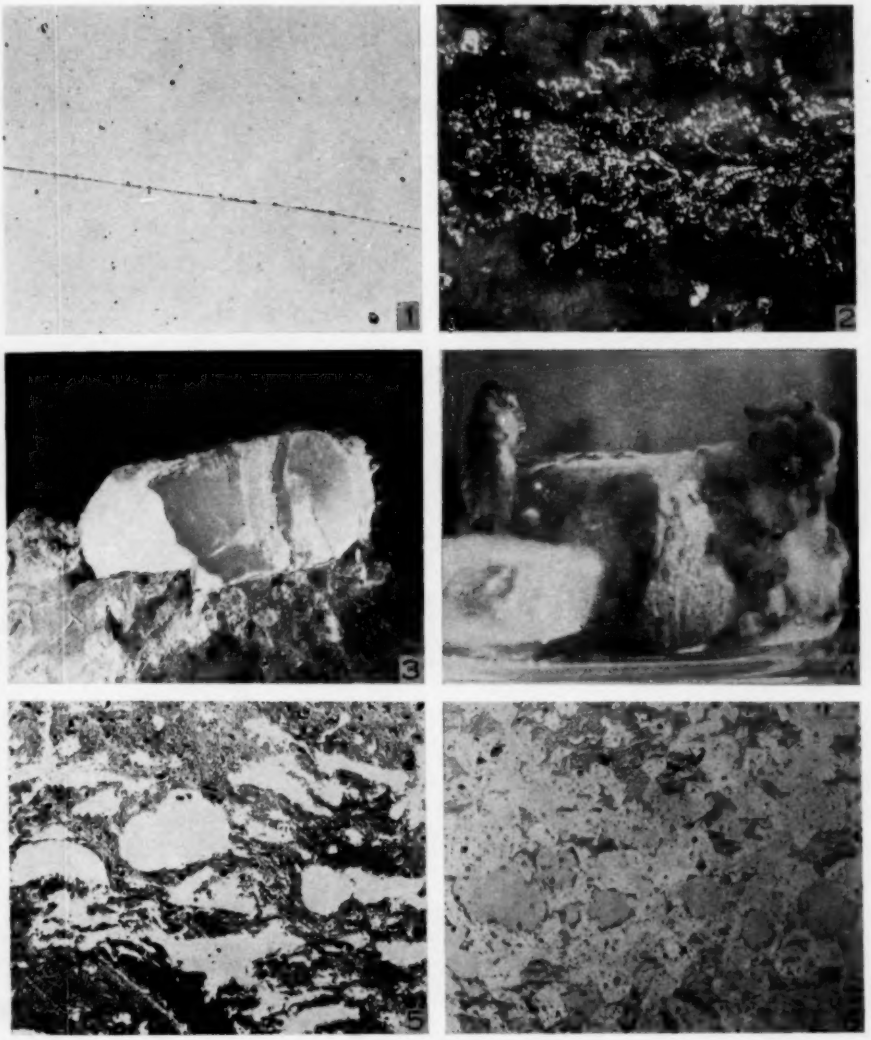

Fig. 1-6 Photomicrographs

Fig. 1. Polished surface of Nevada opal, unetched, Reflected light. Mag. 80X.

Fig. 2. Nevada opal, same field as Fig. 1, surface completely etched by 10 percent NaOH, 1 hour, 50 C. Reflected light. Mag. 80X.

Fig. 3. Small sample of Navada opal after 2 months in neat soda-rich cement paste showing reaction rim of (dried) gel. Reaction rim may be seen as a thin white border on right side and as a broad white area on left surface of broken opal sample. The latter is still partially embedded in hardened neat cement paste. Mag. 2X.

Fig. 4. Small sample of opaline chert after 8 months in clinker extract solution No. 3, 20 - 25 C. Heavy growths of gel-like material may be seen covering right side of sample and extending above surface of sample at both right and left ends. (White area in lower left corner is a specimen of calcite.) Mag. 2X.

Fig. 5. Polished surface of opaline chert, moderate etch by extract solution No. 1, 8 months, 20 - 25 C. White areas are unetched chalcedony; gray areas, opal; black, holes. Reflected light. Mag. 80X.

Fig. 6. Polished surface of Si-Mg limestone, moderate etch by extract solution No. 3, 8 months, 20 - 25 C. Light colored areas are unetched calcite, dolomite and chalcedony; gray areas, opal; black, holes. Reflected light. Mag. 80X.

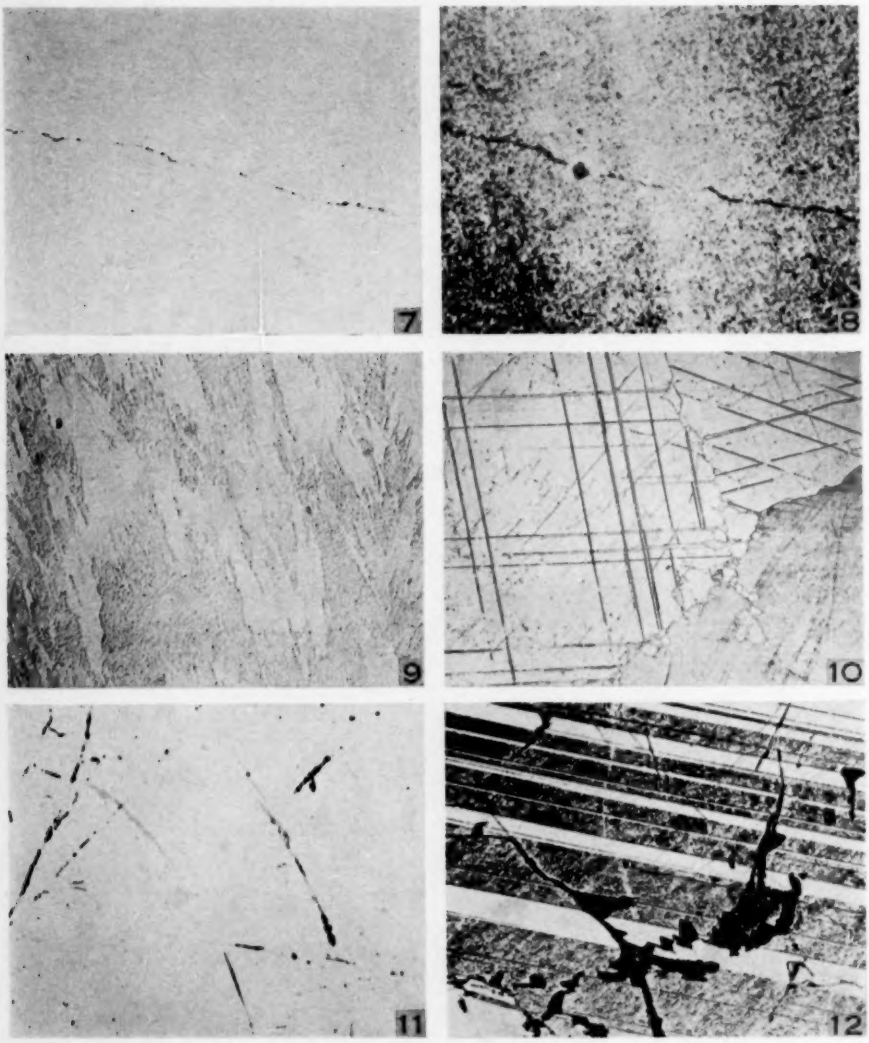

Fig. 7-12—Photomicrographs

Fig. 7. Polished surface of chalcedony, unetched. Reflected light. Mag. 80X.

Fig. 8. Chalcedony, same field as Fig. 7, strong etch by 10 percent NaOH, 3 hours 90 C. Reflected light. Mag. 110X.

Fig. 9. Polished surface of chalcedony, slight etch by extract solution No. 1, 9 months, 40 C. Note differential etching of fibrous grains. Reflected light. Mag. 240X.

Fig. 10. Polished surface of dolomite, slight etch by 10 percent NaOH, 1 hour, 50 C. Note differential etching of twin lamellae and various grains. Reflected light. Mag. 33X.

Fig. 11. Polished surface of bytownite feldspar, unetched. Black areas are cracks and holes. Reflected light. Mag. 80X.

Fig. 12. Polished surface of bytownite feldspar, slight etch by extract solution No. 3, 9 months, 40 C. Differential etching of twin lamellae. Black areas are holes and cracks. Reflected light. Mag. 80X.

Opaline chert

Cherty-appearing brown opal from San Luis Obispo and Paso Robles, Calif., was etched in the 10 percent $NaOH$ and saturated $Ca(OH)_2$ solutions, with similar results to those obtained with Nevada opal. The clinker extract solutions gave the following results at temperatures between 20 and 25 C; the potassium-rich solution (No. 2) completely etched the opal surface with gel formation in 10 days, the sodium-rich solution (No. 3) etched the surface moderately in 2 months and completely with abundant gel formation in 8 months (Fig. 4), and the low alkali solution (No. 1) etched the surface moderately after 8 months (Fig. 5).

Siliceous magnesium limestone

A limestone containing 5 to 10 percent of opal and an equal amount of chalcedony, which occurs near Paso Robles, Calif., was etched in $NaOH$ and $Ca(OH)_2$. The opal in this rock was etched similarly to the Nevada opal. The carbonate (calcite and dolomite) portion of the rock was etched moderately in 2 hours at 60 C, while the opal surface was etched completely. The opal was etched also by the three extract solutions; strongly with gel formation in the potassium-rich solution in 8 months, moderately in the sodium-rich solution in 8 months (Fig. 6) and very slightly in the low alkali solution in 8 months. The calcite-dolomite part of this rock appeared to be unetched by these three solutions at room temperature.

Chalcedony

Chalcedony was not visibly etched in any of the solutions at room temperature, but in $NaOH$ and KOH at 90 C for 3 hours the surface was strongly etched and deeply pitted. In $Ca(OH)_2$ and the three extract solutions at 40 C for 9 months a very slight etch occurred, making the fibrous structure visible (Fig. 7, 8 and 9).

Quartz and chert

Specimens of quartz and of chert composed of microcrystalline quartz were not etched by any etchants at any temperature or in any time periods so far tried.

Feldspars

Three different feldspars, microcline (potassium-feldspar), oligoclase (sodium-rich feldspar) and bytownite (calcium-rich feldspar), were tested in all of the etchants and found to be unaffected at room temperature. At 40 C, however, in the three clinker extract solutions and saturated $Ca(OH)_2$, after 9 months a slight etch made twinning lamellae and grain outlines visible on the polished surface. This was best shown by the bytownite feldspar (Fig. 11 and 12).

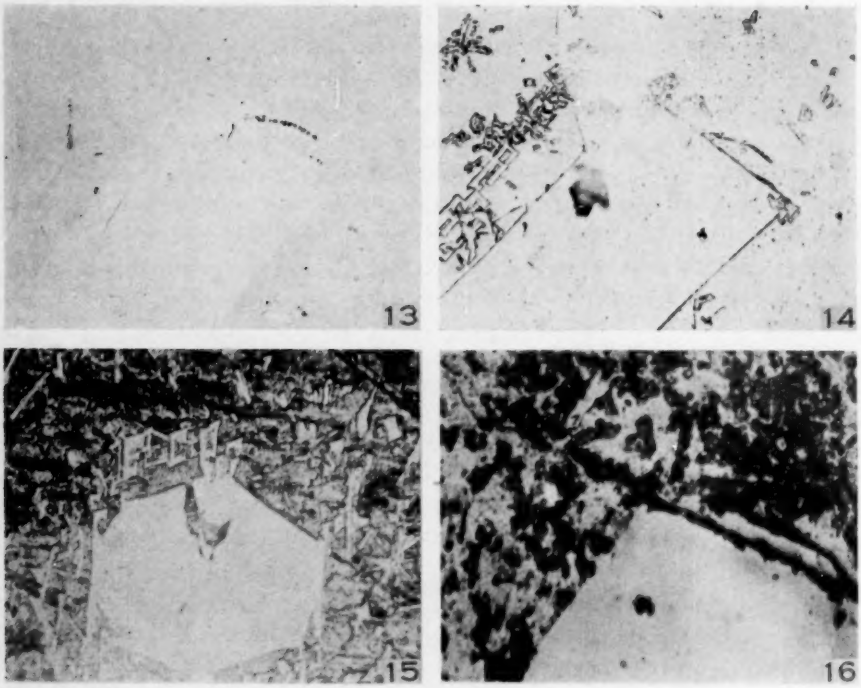

Fig. 13-16—Photomicrographs

Fig. 13. Polished surface of pitchstone, unetched. White areas are feldspar; light gray, glass; black, holes. Reflected light. Mag. 180X.

Fig. 14. Pitchstone, same field as Fig. 13, slight etch by 10 percent NaOH, 2 hours, 60 C. Volcanic glass surface etched. Small piece of feldspar has chipped out and an area of internal reflection has developed outward from this area. Reflected light. Mag. 180X.

Fig. 15. Pitchstone, strong etch by saturated $Ca(OH)_2$, 9 months, 40 C. Light areas are unetched feldspar; dark, etched glass. Reflected light. Mag. 240X.

Fig. 16. Polished surface of Parker andesite, strong etch by 10 percent K_2SO_4, 8 months, 20 - 25 C. Light areas are feldspar; dark, etched glass. Reflected light. Mag. 240X.

Hornblende

Hornblende was not etched by *NaOH*, $Ca(OH)_2$ or the three extract solutions. Experiments were made on single crystal fragments as well as rocks containing small crystals of hornblende.

Glass-bearing rocks

Specimens of obsidian, pitchstone, glassy rhyolite, and the glass-bearing Parker Dam andesite (for a description of these rocks, see Table 1) were treated with the various etchants. A slight etch of the surfaces of the glassy constituents (Fig. 13 and 14) was apparent in as little as 1 hour at 50 C in *NaOH* and *KOH*, but the etching progressed slowly with longer time intervals. At 90 C a strong etch was produced. The clinker extract solutions and neat cements etched the glass slightly

but not in less than 2 months. In the extract solutions at 40 C strong etches (Fig. 15) were developed in 9 months. The K_2SO_4 solution etched the glass of the Parker andesite (Fig. 16), but did not affect the other three glassy rocks. Saturated $Ca(OH)_2$ solution etched at 40 C only after several months. No gel formation occurred on any of these volcanic rocks in any of the etchants.

The variation in chemical composition of the glass phase in andesite, rhyolite and obsidian may account for the observed etching differences (Table 2) among the glass-bearing rocks present.

Phyllite

Fine-grained phyllite, used in the construction of Buck Dam, Virginia, and composed of microcrystalline quartz, mica, calcite and chlorite, was subjected to all the etching tests, but no recognizable etching resulted. The phyllite, however, took such a poor polish that a slight etch might have occurred without detection.

Serpentine

Serpentine showed no recognizable etch in *NaOH* or extract solutions Nos. 1 and 2 (low alkali and high potash). The serpentine, however, had a texture which made production of a highly polished surface impossible.

Calcite and dolomite

Specimens of calcite and dolomite were definitely etched by *NaOH* in 1 hour at 50 C (Fig. 10) and the polished surface was roughened completely in 17 hours at 50 C. A slight etch was developed in neat potassium-rich cement paste in 2 months. The solution of $Ca(OH)_2$ had no effect on calcite, but it etched dolomite very slightly after 9 months at 40 C. Dolomitic limestone from Norwood, N. Y., was not etched by the extract solutions, but was slightly etched by $Ca(OH)_2$ at 40 C in 9 months.

IV. DISCUSSION

Opal is the only material tested which is readily reactive in alkali solutions. It is completely broken down into a gel in relatively short periods and at temperatures below 50 C in *NaOH*, *KOH*, alkali clinker extract solutions and in neat alkali-rich cement pastes. The immediate reaction product is a sodium or potassium silicate solution or gel.

Although volcanic glass is slightly soluble in alkali solutions, only a small percentage of the glass is dissolved and no gel is formed even after several months at temperatures as high as 40 C.

A few other substances, namely, some feldspars and chalcedony, are slightly etched after long periods at 40 C, but microscopic examination

TABLE 2—ETCH TESTS IN ALKALI AND K_2SO_4 SOLUTIONS, CLINKER EXTRACT SOLUTIONS AND NEAT ALKALI-RICH CEMENT PASTES

Solution	Time	Temp. °C.	1 Opal*	2 Opaline chert	3 Si-Mg limestone: opal fraction	4 Chalcedony	5 Quartz	6 Chert	Feldspars: 7 Microcline	Feldspars: 8 Oligoclase	Feldspars: 9 Bytownite	10 Hornblende	Glass-bearing rocks: 11 Obsidian	Glass-bearing rocks: 12 Pitchstone	Glass-bearing rocks: 13 Rhyolite	Glass-bearing rocks: 14 Andesite	15 Phyllite	16 Serpentine	17 Calcite	18 Dolomite	19 Dolomitic limestone	20 Si-Mg limestone: carbonate fraction
10 percent *NaOH*	1 hr	25	No**			No	No	No	No	No	No		No	No	No	No	No		No	No		
	20 min	50	S			"	"	"	"	"	"		"	"	S		"		S	S		S
	1 hr	50	C	M	M	"	"	"	"	"	"		S	S	S	S	"		S	S		M
	2 hrs	60		C	C	"	"	"	"	"	"	No					"	No	C	M		
	17 hrs	50				"	"	"	"	"	"		Str									
	3 hrs	90				Str	"	"	"	"	"											
10 percent *KOH*	1 hr	25	No			No	No		No	No	No		No	No	No	No						
	20 min	50	S			"	"		"	"	"		"	"	"	No?						
	1 hr	50	C			"	"		"	"	"		S	S	S	S						
	2 hrs	60				"	"		"	"	"		S	S		S						
	17 hrs	50				No?	"		"	"	"		S	S		S						
	3 hrs	90				Str	"		"	"	"		M			M						
Sat. $Ca(OH)_2$	17 hrs	50	No			No	No	No	No	No	No		No	No			No					
	8 hrs	90	"	No	No	"	"	"	"	"	"	No	"	"			"		No	No	No	No
	2 mos	20–25	"			"	"	"	"	"	"		"	"					"	"	"	"
	8 mos	20–25				"	"		"	"	"	"	S	S					"	"	"	"
	3 mos	40	S	S	S	"	"		"	"	"	"	M	Str						S	S	
	9 mos	40	Str	Str	M	S					S											
10 percent K_2SO_4	1 hr	50	No			No	No	No	No	No	No		No	No	No	No						
	2 hrs	60	No?			"	"	"	"	"	"		"	"	"	S						
	17 hrs	50	S			"	"	"	"	"	"		"	"	"	S						
	3 hrs	90	S			"	"	"	"	"	"			"	"	M	No					
	2 mos	20–25	M			"	"	"	"	"	"			"	"	"						
	8 mos	20–25	Str			"	"	"	"	"	"					Str						

(Table 2 continued on opposite page)

(Table 2 continued from opposite page)

			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Extract solution No. 1 (low alkali)	10 days	20–25	No	No	No	No	No		No	No	No	No	No	No			No	No	No	No	No	No
	50 days	20–25	"	"	"	"	"		"	"	"	"	"	S			"	"	"	"	"	"
	8 mos	20–25	No?	M	S	"	"		"	"	"		No?	M			"	"	"	"	"	
	3 mos	40	M			"	"		"	"	S			Str			"					
	9 mos	40	Str			S	"		S	S	S											
Extract solution No. 2 (high *K*)	10 days	20–25	C+G	C+G	S	No	No		No	No	No	No	No	No			No	No	No	No	No	No
	50 days	20–25			Str	"	"		"	"	"	"	No?	S			"	"	"	"	"	"
	8 mos	20–25			C+G	"	"		"	"	"		S	M			"					
	3 mos	40				"	"		"	"	"			M			"					
	9 mos	40				S	"		"	"	S			Str			"					
Extract solution No. 3 (high *Na*)	10 days	20–25	S	No	No	No	No		No	No	No	No		No			No		No	No	No	No
	50 days	20–25	S	M	"	"	"		"	"	"	"		"			No		"	"	"	"
	8 mos	20–25	C+G	C+G	M	"	"		"	"	"			S			"					
	3 mos	40				"	"		"	"	"			M			"					
	9 mos	40				S	"		"	S	S			Str			"					
Neat cement paste (1.1% Na_2O)	2 mos	20–25	C+G			No	No		No	No	No		S	S			No					
Neat cement paste (1.2% K_2O)	2 mos	20–25	C+G			No	No		No	No	No		S	S			No		No?	S		

*See Table 1 for source and description of rocks and minerals etched.

**Key to symbols:

No = no apparent etch of polished surface.

No ? = a very slight etch might possibly be present.

S = slight etch; minute pitting or graininess of surface, twinning bands and individual crystals differentiated.

M = moderate etch; approximately one-half of polished surface pitted or roughened.

Str = strong etch; most of polished surface pitted and dissolved.

C = complete etch; original polished surface completely dissolved.

C+G = complete etch with gel growths on surface and sides of specimen, or (in hardened neat cement pastes) with reaction rims of gel-like material.

of a polished surface is necessary to determine this etch even after 9 months. It is doubtful whether the reactions indicated by such slight etches have important significance. Chalcedony, however, is strongly etched in sodium or potassium hydroxide solutions after a few hours at 90 C.

Calcite and dolomite are moderately etched in 10 percent *NaOH* at 50 C and dolomite is slightly etched in $Ca(OH)_2$ at 40 C after 9 months. The reactions of these minerals with *NaOH* and *KOH* solutions are approximately as vigorous as those of volcanic glass. Calcite and dolomite, however, are not dangerous constituents of aggregates because, obviously, a silicate gel cannot be one of the reaction products. The association of gel with the deleterious expansion of concrete, prepared from a high-alkali cement and aggregates containing opal, has been established.

In comparing the reactivity of the different etching media it is seen that similar etching results are obtained with 10 percent *NaOH* solution, 10 percent *KOH* solution, clinker extract solutions, and embedment in either neat sodium-rich or potassium-rich cement pastes. The *NaOH* and *KOH* solutions, however, react much more rapidly than the other etchants.

In general, saturated $Ca(OH)_2$ solutions did not react with the aggregate materials in short-time tests* even at high temperatures (90 C) or in long-time tests at low temperatures (8 months at 20 - 25 C). During long periods at somewhat elevated temperatures (9 months at 40 C), however, many of the aggregate materials are etched. Some of the etching observed in cement extract solutions, especially in the low alkali solution, may be due to the action of the $Ca(OH)_2$ present in those solutions.

Increasing the temperature of the hydroxide solutions greatly speeds the reactions producing an etch on the polished surfaces of immersed minerals. With opal at temperatures of 60 - 90 C, the surface is etched completely and masses of gel are formed in hours, whereas days are required at room temperature. In *KOH* solution, volcanic glass surfaces were etched more in 3 hours at 90 C than in 17 hours at 50 C. Chalcedony appears to be more affected than opal or volcanic glass by the temperature of the etchant. Thus, in *NaOH* at room temperatures not the slightest etch is apparent after 8 months nor is an etch developed in 17 hours at 50 C, but at 90 C complete roughening and pitting of the surface occurs in 3 hours.

*An exception to this was the small sample of opaline shale, submitted by W. C. Hanna, to which reference was made previously. There was not sufficient material to obtain a check test.

V. SUGGESTED TEST FOR REACTIVITY OF AN AGGREGATE

In view of the need for a simple test for detecting potential reactivity of a given aggregate with the alkalies in cements, the following procedure, based on the experiments in sections III and IV, is suggested. Immerse polished specimens of the various rocks and minerals composing the aggregate in a 10 percent *NaOH* solution maintained near 50 C for 18 to 24 hours. Examine the polished specimens for evidences of etching. If etching has occurred, determination, presumably petrographic, should be made for the presence of calcite or dolomite. If neither is present it can be concluded from the etch that the aggregate is potentially reactive with alkalies and should be subjected to critical physical tests in concrete before being used with any but low-alkali cements.

The temperature and concentration of the suggested test solution seem high enough to give in a few hours a reaction that might take months in a set or setting cement. The test produces an etch on calcite and dolomite that may be disregarded inasmuch as the alkali-aggregate reactions which result in expansion and disintegration of concrete all appear to involve silica or silicate materials.

This test has been applied to the following aggregates (see Table 3):

(a) Aggregates classed from job use as reactive.
Bill Williams, Arizona (Parker Dam).
Cowlitz River, Washington.
Spokane, Wash.
Paso Robles, Calif.
San Luis Obispo, Calif.
Buck Dam, Va.

(b) Aggregates classed from job use as non-reactive.
Potomac River, Md.–Va.
Kutras, Calif. (Shasta Dam).
Bethany Falls, Mo.
St. Louis County, Mo.
Reading, Mo.
Camden, Tenn.
Tishomingo, Miss.

In general, the proposed reactivity test has given results paralleling the actual service records of the aggregates.

(a) Aggregates classed from job use as reactive

Definite etches were formed on specimens from four of the six aggregates which have caused actual distress in service. Strong etching and gel formation occurred on the opaline chert from Paso Robles and on the opal in the siliceous dolomitic limestone from San Luis Obispo as described previously (Table 2). Volcanic glass surfaces on various specimens from the Bill Williams and Cowlitz River aggregates were

TABLE 3—ETCH TESTS ON ROCK SPECIMENS FROM VARIOUS AGGREGATES IN 10 PERCENT NaOH SOLUTION

Name and source of aggregate Type of rock	Amount present in aggregate; approximate percentage.	*Conditions and results of tests*
Aggregates classed from job use as reactive.		
Bill Williams gravel, Arizona (Parker Dam)	*percent*	*7 hours 50°C*
Andesite (with interstitial glass)	10	Moderate etch of glass
Andesite porphyry (with interstitial glass)	10	" " " "
Rhyolite (silicified groundmass)	10	Very slight etch (?) of groundmass
Cowlitz River gravel, Washington		*17 hours 50°C*
Feldspathic sandstone	13	No etch
Volcanic breccia (with glass)	13	Moderate etch of glass
Volcanic breccia (no glass)	13	No etch
Greenstone	4	"
Volcanic conglomerate (no glass)	8	"
Trachyte (with interstitial glass)	59	Moderate etch of glass
Andesite (no glass)	59	No etch
Andesite (with interstitial glass)	59	Moderate etch of glass
Monzonite (no glass)	3	No etch
Spokane gravel, Washington[a]		*17 hours 50°C*
Calcareous quartzite	49	Slight etch of calcite
Micaceous quartzite	49	No etch
Siliceous limestone	49	Slight etch of calcite
Biotite argillite	32	No etch
Sericite argillite	32	"
Diorite (no glass)	19	"
Granodiorite porphyry (no glass)	19	"
Paso Robles, California		*2 hours 60°C*
Si-Mg limestone (with opal)	100	Complete etch of opal
San Luis Obispo, California		*2 hours 60°C*
Opaline chert	100	Complete etch
Buck Dam, Virginia		*17 hours 50°C* *3 hours 90°C*
Phyllite	100	No etch No etch
Aggregates classed from job use as nonreactive		
Potomac River gravel, Maryland-Virginia		*17 hours 50°C* *3 hours 90°C*
Chert	11	No etch No etch
Kutras gravel, California (Shasta Dam)		*6 hours 50°C* *17 hours 50°C*
Basalt (no glass; 1-2% of a zeolite)	4	No etch Slight etch of zeolite
Greenstone	18	" No etch
Chert breccia	6	" "
Volcanic breccia (no glass)	5	" "
Diorite (no glass)	8	" "
Serpentine	5	" "
Bethany Falls, Missouri		*17 hours 50°C*
Nodular limestone	100	Very slight etch of calcite
St. Louis County, Missouri		*17 hours 50°C*
Limestone	100	Very slight etch of calcite
Reading gravel, Missouri		*17 hours 50°C*
Brown cherts (3 different types)	95	No etch
White chert	95	"
Camden, Tennessee		*17 hours 50°C* *3 hours 90°C*
Novaculite (chert; no chalcedony)	100	No etch No etch
Tishomingo gravel, Mississippi		*17 hours 50°C* *3 hours 90°C*
White chert (no chalcedony)	50	No etch No etch
Gray chert (with chalcedony)	50	" Slight etch
Brown chert "	50	" "
Banded chert "	50	" "

(a) Many pebbles of this aggregate had calcareous surface coatings containing a small amount of opaline silica. The coatings were lost in preparing the specimens for the etch tests.

moderately etched (Table 3). The reactive constituent in the Spokane aggregate appears to be opaline silica present in calcareous surface coatings on some of the pebbles. The coatings were not preserved on any of the specimens tested and, consequently, only a slight etch on calcite has been noted for this aggregate (Table 3). The Buck Dam phyllite, as already mentioned, takes so poor a polish that a slight etch could easily have been overlooked.

(b) Aggregates classed from job use as non-reactive

No evidence of etched surfaces was found on any of the aggregates with good service records with the exception of a slight etch of the calcite in the Missouri limestones (Table 3) and a slight etch of a zeolite present to the extent of 1 percent in one pebble of basalt in the Kutras aggregate (Table 3).

VI. CONCLUSIONS

A description is given of a rapid etching method for identifying aggregates which may be expected to be reactive when combined with a high-alkali cement. Good agreement is found between the results of this test and aggregates classed as reactive from service records. The method is limited to aggregates which are sufficiently dense and tough to take a good polish.

Discussion of this paper should reach the ACI Secretary in triplicate by April 1, 1944 for publication in the JOURNAL for June 1944.

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Discussion of a Paper by Parsons and Insley:

Alkali Etching Tests on Concrete Aggregates*

By THOMAS E. STANTON

The etching test described by Parsons and Insley has considerable merit for classifying rocks or minerals with relation to opal content and potential reactivity. However, the practicality of this method of analysis for routine control tests has yet to be demonstrated. The authors state that "in selecting aggregate materials for etching studies, rocks were primarily chosen which had been suggested as being susceptible to attack by alkalies."

The difficulty in applying this test as routine consists in selecting the rock particles for the etching test, particularly when as in the California case only two to five per cent of the total aggregate may be reactive. It would be very easy to miss the reactive material entirely unless of an easily detectable type.

A description of some California studies with regard to this test procedure will be found in the 1943 Proceedings of the A.S.T.M., page 877.

The authors have included several tables showing the etching characteristics of a number of rocks and minerals. The publication of data of this nature is very worthwhile, constituting as it does a valuable addition to the technical literature on the subject.

*ACI JOURNAL Jan. 1944; *Proceedings* V. 40, p. 229.

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Job Problems and Practice

"JPP" is a means toward realizing more fully than in a limited number of longer JOURNAL contributions, the mutuality of ACI Membership effort to do a better concrete job. In JPP many Members may participate in few pages. So, if you have a question, ask it. If an answer is of likely general interest, it will be briefed here (with authorship credit unless the contributor prefers not). But don't wait for a question. If you know of a concrete problem solved—in field, laboratory, factory, or office—or if you are moved to constructive comment or criticism, obey the impulse; jot it down for JPP. Remember these pages are for informal and sometimes tentative fragments—not the "copper-riveted" conclusiveness of formal treatises. "Answers" to questions do not carry ACI authority; they represent the efforts of Members to add their bits to the sum of ACI Member knowledge of concrete "know-how."

Notes on Concrete in the Southwest Pacific (40-147)

BY C. C. EVERHART*

1. Precast concrete laundry, kitchen and hospital tubs made in New Jersey and California are being used here and with good results—shipped 7000 to 10,000 miles.

2. Some precast concrete work here is done by native black people and by other native races. They mix and tamp the concrete by hand, and in general turn out fine durable work—the chief item, sewer pipe units from one- to five-ft. internal height made in steel molds. The inverts of these pipes are flat so that the ditch bottom floor can be finished flat and level. The extra concrete serves a good economical purpose. No steel is used in small diameter pipe.

3. Precast shower stall floors made in U. S. A., are being used here in officers' quarters.

4. The two finest examples of monumental work on this island are: (1) a small monument to a U. S. Navy cruiser captain who died August 8, 1942, was constructed by members of the 26th Naval Construction

*EDITOR'S NOTE:—These paragraphs (dated Oct. 20, 1943) were not all of Mr. Everhart's letter. He sent a remittance to give him the status of Life Member of ACI (see By-Laws, Art. IV, Sec. 1) and requested that this sum be invested in U. S. Government bonds as a reserve against the advance payment. It may be of interest to other ACI members to know that while most of the Institute's surplus is in U. S. Government bonds a special bond purchase was made, a small fraction of the total, ear-marked as a reserve for Life Memberships, including that of Mr. Everhart. Our Sea Bees correspondent has been an ACI member since 1925. His home address: Moville, Ia.; his military service address: Co. A, 14th Naval Construction Battalion c/o Fleet Post Office, San Francisco, Calif.

Battalion; (2) H. M. Coe, USNR, has done some sculptural work on a flag staff base for the 14th Naval Construction Battalion. Both pieces of work were done in concrete during 1943. Mr. Coe is a Texas sculptor who studied under Carl Milles.*

5. On our island are four reinforced concrete bridges with single, double and triple spans of about twelve feet, constructed by European interests prior to the enemy invasion. Each bridge has three lines of simple beams about 8 by 12 in. in cross section and hard wood sleepers were bolted on these girders and hard wood flooring on the sleepers. These girders have in three cases failed by bending at mid-span. Each beam contains one 2-in. narrow gauge railroad rail which in most cases has pulled squarely in two, leaving a clean square crystalline break. These rails had been wound spirally with barbed wire. There was no spalling of the concrete beneath the rails or to the sides. The tops of the beams showed some crushing of the concrete at mid-span directly above the rail breaks. No top steel or web reinforcing had been used in the beams. Deflection had opened up cracks at the abutments and mid-span supports and in a plane vertical or diagonal to the long axis of the beams. The bridges had probably been greatly overtaxed by heavy military loads. The concrete was of gravel, sand and was of good quality and well placed.

6. I have inspected the concrete floors and foundations of a power-house built on this island by the enemy after invasion and occupation. The work is not bad, but not first class. Our Marines seized the power-house with such speed and secrecy that the engines were never shut down. Our armed forces have continued to operate it.

7. Many hundred miles from this island I inspected bridges and tunnels constructed of stone, granite, steel and concrete from 1902 to 1904. In one bridge abutment precast concrete corner quoin stones had been laid with panels of native cut granite. A cast-in-place abutment cap of concrete had been used plus heavy and elaborate revetments of mass concrete around the abutment and down over the adjacent river bank. All this concrete work shows great durability and the finest of design and workmanship—clearly marked by the influence of a famous European school of bridge engineering.

8. While a patient at a S. W. Pacific Navy Hospital during August, 1943 I observed a short low mass retaining wall under construction on the hospital grounds. I remarked to the ships company carpenter mate that the wall looked like Pennsylvania railroad standards for mass retaining wall construction. The carpenter laughed and said, "My officer is from the Pennsylvania R.R." Next day I passed by again and the carpenter called out, "My officer said to tell the patient that

*At Cranbrook Academy of Art, Bloomfield Hills, Michigan—1930-40—Editor.

he was right and that he had been civil engineer with the Pennsylvania 15 years." Fine work needs no trade marks.

9. Concrete has been used exclusively for grave markers in the official burial grounds on this island for members of the Armed Forces. There are many different designs, many of the markers having been made by friends of the deceased. Here sleep side by side colonel and private, captain and seaman. Some of the concrete markers are inlaid with inscribed brass or aluminum plates made from shell cases or mess gear. Some aviators' graves are marked by a half propeller set in a concrete base.

10. Many months ago underwater breaches were closed in a hit U. S. destroyer by bulkheads built of sacked portland cement concrete. This work was supervised by an officer of one of the first Battalions of Sea Bees to go overseas. With this temporary bulkhead the destroyer limped into a friendly port for further repairs.

Tests on 17-year Old Concrete from Fort Snelling-Mendota Bridge (40-148)

BY WALTER H. WHEELER*

The Fort Snelling-Mendota Bridge, 4,119 ft. long, 12¾ rib arch spans 304 ft. center to center of piers, flat slab deck 60 ft. 8 in. wide one bay wide with overhanging cantilevers, panels 36 by 30 ft., 5 in. (*Engineering News Record* Mar. 31, 1927, p. 514) was opened to traffic Nov. 6, 1926. Immediately before opening four lines of levels were run the full length of the bridge and readings taken at 15 ft. intervals. These levels were repeated Aug. 29, 1932 (*E. N. R.* Sept. 29, 1932, p. 371) and again on Nov. 17, 1932 (*E. N. R.* Mar. 30, 1933, p. 415). Very little change had occurred due to shrinkage or "flow" of the concrete and no settlement of piers.

Early in November 1943, the Minnesota State Highway Department, which now controls the bridge, cut a hole through the flat slab floor of the bridge in connection with the installation of navigation lights. This hole was cut in the north gutter of the roadway, which is exposed to the direct rays of the sun in summer and extreme low winter temperatures. The maximum seasonal temperature range to which the surface of the concrete has been exposed is in the nature of 170 F. This concrete in the gutter has also been exposed to the maximum affect of moisture combined with alternate freezing and thawing.

In cutting this hole the Department took cores of the concrete in the bridge floor slab and had them tested. T. W. Thomas reported the

*Designing and Consulting Engineer, Minneapolis, Minn.

tests to E. J. Miller, Bridge Engineer of the Highway Department, who kindly furnished the writer with a copy, from which I quote:

The cores as received were rather long having a greater ratio of length to diameter than the standard ratio of 2 to 1. They were cut on our carborundum wheel to have a standard ratio. The cut was taken from the bottom of the core since this tended to place the reinforcement close to the end (2 inches away) thus producing the least effect on the strength. The modulus of elasticity was also measured, using the secant method between unit stresses of about 400 and 1100 psi. The tests were made in a saturated condition, the specimens having had ten days soaking before measuring the elasticity and fourteen days before measuring strength.

	Ultimate Strength	Modulus of Elasticity
	psi	psi
	6636	5,600,000
	6430	5,030,000
	6362	4,450,000
	6975	5,070,000
Average	6601	5,037,000

My records of the job show that this concrete was poured July 12, 1926, using 39 gal. of water per cu. yd. of concrete (equal to 6½ gal. per sack) and that the consistency of the concrete was "good". The gravel and sand tests of that date show as follows:

Gravel		*Sand*	
Passing 1 in. mesh screen	100 percent	Passing ¼ in. mesh screen	100 percent
" ½ in. " "	58 percent	" No. 16 " "	55 percent
		" No. 30 " "	17 percent

Tests of the cement received on the job at that time, which are undoubtedly representative of the cement used in the bridge floor slab from which the Highway Department took the cores averaged as follows:

Initial set	2 hr.	29 min.
Final "	5 "	54 "
Residue on 200 sieve		19.5
Steam pat		O. K.

	7 day		*28 day*	
	A.	B.	A.	B.
Tensile strength psi	347	342	459	435

Test cylinders taken from the concrete being placed in the bridge floor slab at about the same time that this slab concrete was placed, showed as follows:

	Maximum	*Minimum*	*Average*
Compressive Strength psi 28 days	3120	2763	about 2940

It will be seen that the four cores recently tested at the age of 17 years and 4 months, averaged a little more than twice the 28 day compressive strength of the concrete used in the floor slab.

This recent test is also a rather clear indication that the control of the concrete, selection of the aggregates and the specifications covering cement, aggregates, water, mixing, placing and curing of the concrete have been amply justified by the results.